MANUFACTURED IN U. S. A.

PHYSICS

The Science of the Forces of Nature

BY

D. W. HERING
Professor Emeritus of Physics, New York University

P. F. COLLIER & SON COMPANY
NEW YORK

PREFACE

"Be not the first by whom the new are tried,
Nor yet the last to lay the old aside."

THE poet's injunction is especially fitting for the man of average intelligence who would like to keep up with the rapid strides of science in the progress of civilization. This is markedly true in connection with the science of physics. He could steer a safer course if he could only distinguish between the flights of enthusiasm which carry the scientist beyond the actual, and the excessive conservatism of the unimaginative which binds him to old ideas that have really been superseded. From incoherent and bewildering newspaper accounts of Einstein and the theory of relativity he trembles for the law of gravitation and feels that his foothold upon earth is no longer secure; wireless communication is exploited so wildly that his brain whirls; the "movie" astonishes and fascinates him and he wonders how it is done; the phonograph, either with or without the telephone, multiplies his pleasures and his means of culture; and he feels helpless as he contemplates these marvelous achievements. Then he reads that old theories of life have been exploded and that all phenomena of physics must be judged from a new viewpoint.

In all this what he most needs is a balance wheel—something that will help to steady him while he is adjusting his view to the new positions.

This book is not an attempt to elaborate the fine points of theories old or new, but it endeavors to show what physics is and how it has come to be what it is; to state simply and rationally the principles on which interesting and important phenomena rest; and to show that many apparently simple things which have become commonplace in our daily life are thoroughly scientific in their nature, and have become necessaries to us by intelligent appreciation of their scientific character. We could not think of dispensing with present-day household conveniences, with refrigerating processes, with modern illuminating, and a thousand like wonders, and the thoughtful man would like to know, if possible, how they are brought about. To tell this in a way that does not call for technical ability on the reader's part is the aim of this work. The task is too large to be achieved fully in so small a compass, but it is hoped that enough has been accomplished to be of real service to the man who "wants to know."

D. W. H.

CONTENTS

PART I

PRELIMINARY VIEW OF PHYSICS

PART II

ELEMENTS OF PHYSICS

LIST OF ILLUSTRATIONS

PART I

PRELIMINARY VIEW OF PHYSICS

CHAPTER I

THE SCIENCES

SCIENCE AND ART

A FAMILIAR aphorism states that "a principle of science becomes a rule of art." This work assumes that civilization is the application of knowledge to conditions of living; and it proceeds upon the thesis that the sciences are the principles and the arts are the practices of civilization—meaning not simply the "fine arts," but commercial and industrial arts also—the art of shipbuilding, of weaving fine fabrics, or of sharpening scissors.

With increase of knowledge the number of sciences increases, each one usually having a foundation principle, or possibly several such principles. Sometimes one principle is so broad and comprehensive as to constitute a doctrine out of which, in a general way, the whole science may be unfolded. Such is the doctrine of evolution or the doctrine of the conservation of energy. On the other hand, a principle of science is sometimes a very simple relationship.

But a science does not begin with known principles. Some sort of practical experience, clumsy and

crude perhaps, always precedes the elucidation of the principles upon which the practice really depends, and which make subsequent practice more intelligent and satisfactory.

It is not only in large industrial and commercial operations that the march of civilization is to be traced. Applications of physics to relieve the hardship and tedium of domestic drudgery claim a front rank in that same march, and many small operations have been made practicable by the availability of the electric motor. Electricity has become a word to conjure with, and many machines and processes have been proclaimed as "electrical" to capture the interest of the buyer or user when there is nothing electrical about them except the motive power; hand power or horse power or water power would produce precisely the same result. Shoes are mended, hats are renovated, hair is cut, all by electricity as per announcement, and the real technical part of the operation is lost sight of in the glamour of this alluring agency. The realities of scientific progress are remarkable enough to need no such specious pretenses. The electric light has taken the place of the tallow dip; the farmer freely uses the power tractor for cultivating his land and the automobile for his traveling and trucking; while in the house, mechanical dishwashers, vacuum cleaners, and machines for heating, cooking, laundering, etc., are familiar servants.

A special impetus is given to the development of science along certain lines that are determined by some circumstances of immediate national importance or necessity. The exigencies of the World War brought aviation forward more rapidly than would have been probable if peace had been maintained,

and also stimulated the chemistry of gases and explosives.

The interpretation of the principles underlying a science, however, is usually due to some intellectual genius, who imposes upon the science a form for its future and gives a trend to the course that will be followed, perhaps for a long time. It was so in earlier times; and when various peoples were breaking the bondage of the Dark Ages, Newton's method of generalizing mechanical principles fixed the line along which mechanics as a science progressed for many years. The basis, in his case, was the effect of a force taken in connection with the length of time it is in action, i. e., the impulse; but another line proceeded from the consideration of the force to overcome a resistance in conjunction with the distance through which the resistance was moved: i. e., the work done. This was the plan followed by the great Dutch physicist, Christian Huygens (1629-1695), and while the Newtonian method was most fruitful in mechanics proper, the Huygenian mode of approach is more characteristic of modern physics in general. Of course, both methods deal with the actual relations and actions of bodies and forces. Both ways of proceeding and their significance are given in some detail in the text following.

"The Newtonian method is apparently in harmony with the oldest practice. A recent writer thinks that the development of mechanics by the ancients, and their massive constructions, was governed by force in connection with time, because they had a superabundance of both. Time was of no value to them, and slave labor was at their command without limit." (*Technik des Alterthums;* Dr. Albert Neuburger, Leipzig, 1919.)

SCIENCES DISTINGUISHED FROM ONE ANOTHER

The subject of this work is not supposed to include vital processes, or mental actions, or spiritual affairs, but only what is ordinarily understood as the world of nature in a material sense. The phenomena of the material world are systematically disposed in various sciences, two of which, chemistry and physics, are closely related to each other.

Any portion of matter collected together is a body, and bodies may differ as to the material that composes them. The material of a body—water, for example—may lose its identity by being changed into constituents, forming other bodies of different material, or it may be changed by being united with some other form of matter to constitute a different body. Phenomena which are comprised in the form, or transformation, of matter belong to the science of chemistry.

But besides the material of which bodies are composed, there is associated with them another entity that is capable of being examined, of being augmented or reduced, of having various forms and of being changed from one form into another that has commercial value, can be bought and sold, but which is not matter; it is Energy. What energy is, ultimately, we cannot tell, any more than we can tell the ultimate nature of matter, but we can tell much as to its qualities, its effects, and the circumstances that attend it—always, however, in connection with matter.

CHAPTER II

THE REALM OF PHYSICS

TAKE any set of bodies, anyhow arranged: they may be regarded as a system of bodies, and their mode of arrangement, relatively to one another, is the "configuration" of the system. At a given instant they have a definite condition as to temperature, motion, and physical state in general, by which they influence one another, and through some interaction among them the configuration of the system will be changed. That means that at least some of the bodies will have changed in position, or their physical state is altered; and the capability which any body has of changing another body is called "energy." A sunbeam falling upon a lump of ice may melt it, and the capability of so doing is energy of the sunbeam; the cord of a bent bow when released is made to propel the arrow by the straightening of the bow, and the capability of thus putting the quiescent arrow into rapid motion is the energy of the bow when bent; but the energy that melted the ice is not of the same form as that which propelled the arrow. All bodies are incessantly taking in or giving out energy in some form or other; energy is continually transferred from body to body, entering a body in one form, handed on to another in perhaps a different form, eluding, so far, all efforts to recognize it or perceive it dissociated from matter, but recognized, if at all, by its effecting a change of

some kind in bodies. Matter thus becomes at once the object and the vehicle of energy, and energy is the capability of a body to effect a change in another body. The phenomena of energy in its various forms and transformations constitute the realm of physics: all phenomena of physics, large or small, are transformations of energy of one kind into another kind, or transferences of energy from one body to another body.

PRIMARY CONCEPTS

Our view of the universe and of all that occurs in it is embraced in three so-called primary concepts: space, time, and matter. They are called primary because they cannot be defined in terms that are any simpler or any easier to understand than the names themselves by which they are known.

The concept of space is that by which we decide the place of an object or an event. We are conscious in our own persons, and we ascertain, by extending our limbs, that one object is situated differently from another, relatively to ourselves; and, by going about, we come to realize that there is an indefinitely extended region in which different bodies are placed. The term space is used to express the entire range of situation for all bodies, but we do not know of any difference in one portion of space from another portion, except by the fact that different bodies are situated in the different portions.

Again, we are conscious of the fact that events do not occur simultaneously, and that what seems to be the same kind of event occurs repeatedly; that there is a sequence in their occurrence—and this is the basis of our idea of time, but we cannot distinguish one portion of time from another except by the different events that occur in them.

As to matter, of which a limited portion is a "body," our senses in the first instance make us aware of its reality, and give us a conception of it; study and examination give us a systematic acquaintance with it, and finally enable us to predicate matter without the direct evidence of our senses.

In space we may find an answer to the question "Where", in time to the question "When", and in matter to the question "What", and incidentally "How", but never, in all science, an ultimate answer to the question "Why". When all the processes by which energy changes occur, and the various phenomena ensue, whether by light with its pictures, by electricity with its subtle influence, by heat with its power, when they are all, as we say, "explained," the question as to why the agencies should thus act still remains unanswered.

These primary concepts are as old as human consciousness, but the formal, orderly connecting of them in a scheme of Natural Philosophy we owe to Sir Isaac Newton. He says of time: "Absolute, true, and mathematical time, of itself, and of its own nature, flows equably and without regard to anything external, and by another name is called duration. Relative, apparent, and common time is some sensible and external measure of duration by the means of motion, which is commonly used instead of true time; such as an hour, a day, a month, a year." (*Principia.*)

The revolution of the earth around the sun has been so constant that the year is considered a fixed period of duration, and is taken as a proper period for measuring time. The average time required by the earth for its successive rotations upon its axis,

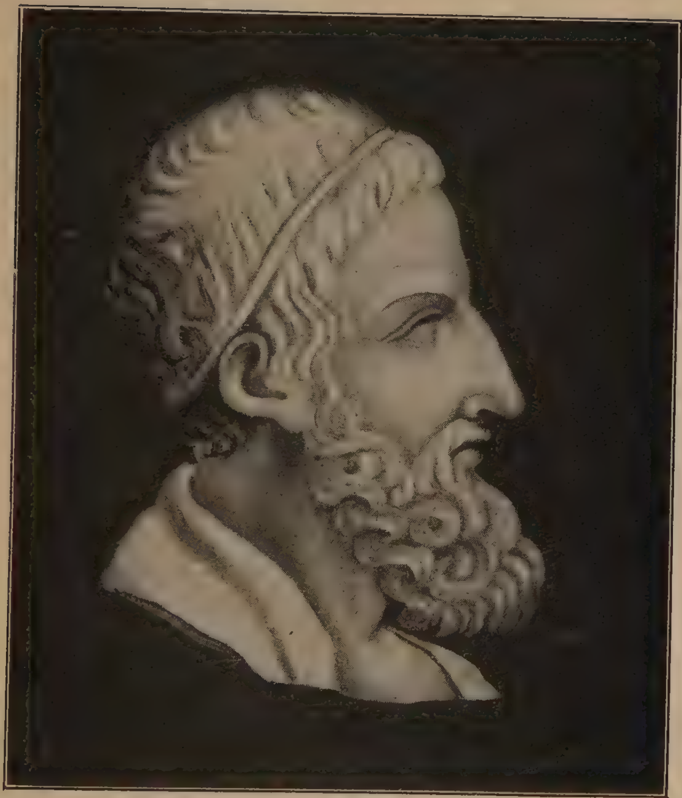
relatively to the sun, is adopted as a mean solar day, which, in turn, is subdivided into hours, minutes, and seconds.

RELATIVITY

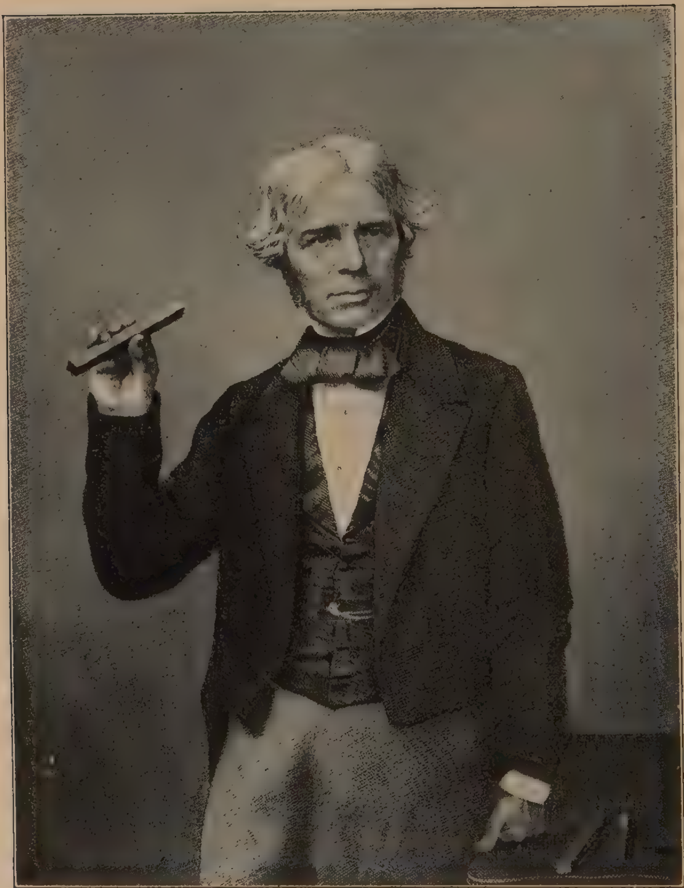
Remembering that physics deals with bodies in which the matter composing them does not change into matter of another kind, there still is much to consider as to the change of form which a body may undergo, without change in the character of the matter composing it.

The three things, space, time, and matter, are called coordinates—a term to express the means by which we locate or determine events; just as, in mathematics, coordinates are measurements by which a point, or line, or other geometric figure is determined. But in mathematics there are various systems of coordinates: polar, employing distances and angles; rectilinear or Cartesian, employing distances from a set of fixed axes of reference; and still others. One system is preferable for some kinds of mathematical problems, and a different system for problems of a different class, the Cartesian system being much the most common in use at this time. So, too, a different system of coordinates might be devised for natural occurrences, and one in which the concept of time as stated above is replaced by a different view of relative events, has been introduced in the doctrine of Relativity.

Newton adopted the idea of absolute time and absolute space which, with matter, gave three stable or fixed bases from which to estimate or locate an event; relativity discards the idea of such an "external" basis either of time or space, but considers that everything is relative; that, inasmuch as there is no fixed basis from which to reckon, all motions



ARCHIMEDES



MICHAEL FARADAY

must be of a relative character, and an object that may appear to one observer as stationary may, to another, seem to be in motion, and vice versa.

If, while an observer stood still, an object swept past him with the speed of light, in a second of time it would be 186,000 miles beyond him; but if, when it was abreast of him, he too moved onward in the same direction with the same speed, he would continue to be right by the side of the object; it would not part from him and if he were not conscious of his own motion, the object would seem to him to be stationary; he and it together might swing round the sun, and he would not know it if he had nothing else to judge by; so far as time is concerned, the year would be nonexistent, and he would not have that unit for the measurement of time. He might, however, be moving at a comparatively slow rate instead of evenly apace with the extremely rapidly moving object, and then his observations of the displacements of this object would not differ materially from what they would be if he were stationary.

Most of our observations, especially those of distant objects, are made by means of light, and if they, or we, are at the same time moving with a speed anywhere near that of light itself, our conclusions must be affected by that fact. This, which was of course recognized long ago, would not alter our calculation, or our observation, of motions or positions of bodies whose movement is not at a rate comparable to that with which light travels. Now, the fastest movement of any large bodies, or indeed of any bodies that are not microscopically small, is not more than forty or possibly fifty miles a second. If two such bodies were moving in opposite directions, their rela-

tive rate of motion would be at most a hundred miles per second, while the speed of light is nearly two thousand times as great as that, so the Newtonian views are quite applicable to all ordinary experiences in physics. It is only with extremely refined problems of an electrodynamic character that the doctrine of relativity would be of any service, and then only as a second or higher order of accuracy, of which the Newtonian concepts afford a first but close approximation.

The present theory of relativity has been developed within the last fifteen years, chiefly through the work of Dr. Albert Einstein of Zürich and Berlin, and of Professor H. A. Lorentz of Leyden. It is interesting, important and far-reaching, but is rather of the nature of a capstone on the structure that had been erected upon the foundations laid by Newton, and that structure, both in its parts and in the principles which hold them together, is none the less valuable because of the possible opportunities the new theory may afford to penetrate intricacies and obscurities of more difficult problems. Our endeavors to acquaint ourselves with the main structure would not be helped, rather they would be made more difficult, by attempting to carry the refinements of this theory where they have no appreciable value.

BRINGING ORDER OUT OF CHAOS

In the seventeenth century ideas of physics underwent a great clarifying. It had been customary to treat the subject philosophically rather than scientifically; to account for the action of nature on the ground that she did as she did because she ought to do so, to conform to the purpose of an all-wise Creator. Then came the study of how bodies really

do act, and an effort to classify their actions according to some method.

Copernicus (1473-1543) had elaborated the present system of astronomy; Kepler (1571-1630) discovered important rules as to the movements of the planets in the solar system; Galileo (1564-1642) investigated with great skill the motions of bodies. It had been thought that the natural state of a body was one of rest; if it were put in motion and left to itself, it would come to rest; all bodies did so, as was plainly to be seen. Galileo discovered that bodies so left to themselves sometimes slackened their speed or stopped. Under other circumstances their speed increased; notably was this last the case with bodies falling to the earth. Out of all accumulated observations—jumbled, confused, chaotic—came the possibility, in the hands of a master, of bringing order and of representing the actions of bodies so precisely and invariably as to constitute "laws." That is what a law of science is: not a statement of how bodies ought to act, or how they must act, but how, under given conditions, they do act.

Sir Isaac Newton (1642-1727) was the great genius that promulgated these laws. Born in the year in which Galileo died, his life kept unbroken the chain of continuous scientific progress, and his work brought into full flower the tree of knowledge that had been fostered by his predecessors and that was to bear abundant fruit from that day to this.

Now came the pronouncement that it was just as "natural" for a body to be in motion as at rest; that if it were at rest it would stay so until some influence outside of itself put it in motion; if it were in motion it would stay so without alteration until some influence external to itself changed its motion. That

this was true of matter in general was comprised in the broad statement that all matter was characterized by inertia. This was Newton's first great generalization.

Later, from the action of bodies on the earth, and the motions of the heavenly bodies, Newton was able to deduce the greatest of all scientific principles, known as the law of universal gravitation. This law, and also the law of inertia, with two other so-called laws of motion, will be further considered in their place in the science of physics.

CHAPTER III

FORMS OF MATTER—ATOMIC STRUCTURE

A BODY of, say, common salt, may be made smaller and finer, even pulverized, and yet each fine particle will be salt; even if it is made so fine that the separate particles require a microscope to magnify them sufficiently to be visible, it is still salt. These minute particles may be dissolved in water, and be so completely separated, and become so small, as to be invisible with the highest magnification that we can bring to bear upon them, yet they will still be salt, and perceptible as such to the taste. And yet these smallest portions can be separated *chemically* into two substances which are quite unlike each other and neither of which is salt. That smallest particle in which the original substance retained its identity is a "molecule"; the constituents of the molecule are "atoms," and so long as an atom can be no further separated into constituents of a different nature the substance composing it is regarded as an "element." Many substances once thought to be elements have been resolved into more elementary parts and are now known to be compound.

Only in connection with electricity and radiation does physics concern itself with parts of matter smaller than the molecule.

But besides the fineness of division to which a body may be subjected, its material may take several

forms, called states of aggregation; e. g., water may be solid, or liquid, or gaseous, ice, water, steam—and yet consist of exactly the same molecules in each state. Such different states are possible for all substances, and most substances may be carried through the three states successively. The theory is that in the solid state the individual molecules of a body are restricted to a very narrowly limited space within which they have some motion, but from which they do not depart; in the liquid state the bonds holding the molecules are greatly relaxed, and the molecules move among one another with perfect freedom, though still attached to one another firmly enough to preserve the integrity of the body; in the gaseous state the bonds holding the molecules together are entirely severed, and the agency, whatever it may be, that has thus dissevered the molecules, has imparted to them a motion so vigorous that they separate from one another as far as the walls of the vessel containing them will permit, and if not retained within such a vessel, they spread out indefinitely, mingling among or uniting with other substances, and thus the integrity of the body that was composed of them is lost.

A perfectly valid distinction of these forms of matter, when taken *en masse*, may be made without reference to molecules. The first division, as to form, is into solid and fluid; and the latter may be divided into liquid and gaseous. Some substances, as wood, or stone, or tallow, will sustain pressure endwise without giving way sidewise, others, like water, or pitch, will not; and we may say that a body that will sustain any longitudinal pressure, no matter how slight, without lateral support, is a *solid*. One that will not thus sustain pressure is a *fluid*.

Any body will give way under sufficient pressure; the point is that some substances will not withstand *any* pressure without support, while others will withstand it up to a certain point. The latter may be classed as solid, the former as fluid. Also, there are some substances that can be poured into a vessel without filling it, while others, like air or illuminating gas, if put into an empty vessel, will fill it, no matter how little is introduced or how large the vessel may be. Hence, a liquid is a fluid with which a vessel may be partly filled; a gas is a fluid which will wholly fill a vessel though but a small quantity is introduced. Under such conceptions a fluid may be harder than a solid.

The idea that matter, in its finest form, consists of atoms is very old, but there has always been much speculation as to the structure of the atom. Even accepting it as the ultimate particle of an element, different theories have been propounded, giving to the atom in some cases a complex structure and a variety of forms. Recent discoveries have gone further and indicate that an atom consists of a very small nucleus with one or more much smaller particles revolving around it. Indeed it is even thought that these two parts of the atom are electricity itself, and, therefore, that the ultimate character of matter is identical with electricity. While such considerations help to account for many striking things in recent physics, such as X-rays and radioactivity, it is not necessary to decide upon their correctness in order to learn the nature and laws even of most electrical phenomena—much less those of phenomena that are not electrical.

CHAPTER IV

DEVELOPMENT OF MECHANICS

EARLY USE OF IMPLEMENTS

THE very earliest instincts of man were undoubtedly directed to procuring for himself food and shelter, and to protecting himself against aggression, whether from animals or alien tribes of human beings. For these purposes his experiences from infancy taught him to erect barriers, to do which required the moving of large stones or logs; and to employ weapons, no matter how primitive in form. It was the use of tools that raised him above the brute. His first use of a stick with which to pry or move objects must have been intuitive, but the rude implement was afterward developed into the mechanical instrument called the lever.

The effectiveness of bodies in motion, in the character of implements, doubtless was learned later, though the use of them as missiles must have come very early in the history of the race. The analysis of these actions, by which the implements could be elaborated and improved, and made more effective, did not precede, but followed, the early and crude discoveries. If accident showed that a heavy stone could be taken up a slope, although it could not be lifted vertically, the use of the inclined plane was certain to follow closely upon that of the lever.

In all cases there was the consciousness of effort in the form of pushing or pulling to lift an object or to overcome a resistance. That effort, which we

recognize as a push or a pull, is the primary form of what we call technically "force."

EARLY PHASES OF MECHANICS

Among the earliest scholars to investigate the scientific principles by which the ancients employed tools or implements was Archimedes of Syracuse (287-212 B. C.), although by his time the mechanic arts had reached a high stage of development. His discussion of the lever, and his appreciation of the enormous gain of force that it produced, gave rise to his famous saying that if he had whereon to rest his fulcrum he could move the world.

That portion of physics which deals with the effects upon bodies when forces are applied to them is designated as "Mechanics." Early mechanics was devoted almost wholly to that phase of the science which considered the relation of forces and bodies that would result in stability, in balancing, or producing equilibrium, and this is called "Statics." The phase which considered motion and the problems connected with it came later and is called "Kinetics." In both these divisions of the subject a great many experiences, widely varied in character, were accumulated before they were so correlated as to be termed scientific.

Whatever may have been the original steps by which the principles were arrived at, we have no need to follow those steps now in presenting the science. The lever, as we are now prepared to treat it, can be put at once in its legitimate place among other appliances in physics, with respect to the principles concerned in its use; and so, too, can other contrivances which have been denominated the "Simple Mechanical Powers."

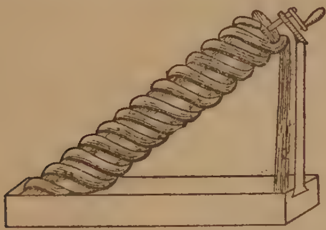
KNOWLEDGE MUST BECOME ORDERLY TO BE SCIENTIFIC

Archimedes as well as many of his early successors in scientific investigation delighted in showing, by a process of reasoning, that natural actions, such as those of the lever, of bodies falling, etc., must of necessity be as they are. These demonstrations are in many instances very clever, sometimes they are good logic, sometimes fallacious, but none is so good evidence as the fact itself, and that is learned in the first place by experience. Then a number of repetitions which show the relationships that are concerned in the action, make it possible to express those relations accurately in numbers, and the action acquires a precision that makes it possible to go ahead, with confidence as to the outcome, and the proceeding then becomes truly scientific.

One of the earliest uses to which machines were put was that of raising water, and here the wonderfully versatile mind of Archimedes was again in evidence. The first applications of machines for this purpose, however, lifted the water directly, and all that the machines accomplished was to make the operation continuous. The chain pump simply passed disks through the cistern and up the delivery pipe, lifting the water that was above them when they entered the pipe at the bottom. Archimedes' screw provided a continuous movement of the water that lay in the lowermost portion of a screw chamber, which was wound spirally or around an inclined axis.

The suction pump was later. In this the early users had no correct notion of the action of the pump. The rise of the piston would leave a vacuum if the water did not rise to follow it. The fact that the

water did so rise was, they said, evidence that "nature abhorred a vacuum." But when it was found that the water would not follow the piston to a height exceeding thirty-three feet, the only explanation was that nature did not abhor a vacuum above thirty-three feet! The whole philosophy was directed to the behavior of water. Afterward it was



THE SCREW OF ARCHIMEDES, USED FOR IRRIGATING IN EGYPT

realized that the range of this "abhorrence" varied with different liquids.

Mechanics, which is the oldest branch of physics, was at first, and for many centuries, developed only in the character of statics. In its early history all science was mixed with philosophy, and then came a period in which practically all learning and teaching was invested in monks or church dignitaries, and were made to conform to church doctrines. Superstition was common, and if a scholar supported an idea that seemed to controvert established religious views, he was held severely to account for it, and popular prejudice was against him. This led sometimes to displays that were comic and results that were tragic. Galileo made discoveries in astronomy so startling and so upsetting that he was considered a heretic, and anything in the way of a

novelty coming from him was viewed with suspicion, if not with derision. Bodies fell, his contemporaries thought, because of their weight—some were heavier than others, so of course they would fall faster—it was ridiculous to think otherwise; so, when he gave a public demonstration, by dropping from the top of the Leaning Tower of Pisa two massive balls, one weighing twice as much as the other, which kept pace with each other throughout their fall, and struck the ground together—instead of convincing the crowd it simply angered them, for they were sure he had deceived them by some hocus-pocus. The scientific explorer took his life in his hand as literally as did Columbus when he sailed into the unknown seas.

The Middle Ages (the "dark ages") were followed by a period of enlightenment, the Renaissance, which marked a revival of learning, and science especially took on a new character. New theories had to be devised to conform to observed facts, and physics as well as other sciences then could grow. Treating science in that way it is now possible to understand how it is that a heavy body falls no faster than a light one. The work of Galileo gave a new starting point in developing mechanics, and it is with the principles which he brought out that we proceed nowadays to trace the relations of force and motion, and by which, in the two succeeding centuries, this subject along with other branches of physics fell into a general scheme of energy.

EARLY ATTEMPTS TO OBTAIN A VACUUM

The physics of the air received slight attention; its force as wind was recognized, and applied in the sailing of ships, but that it had weight like solids and liquids, and that it could be pumped out of a

vessel was not known until the middle of the seventeenth century. Then came an avalanche of experimentation and revelation. Conditions connected with a vacuum were a subject of much interest, but the only known way to have a vacuum was first to have a vessel filled with water, and then, if the water could be taken out without admitting air, a vacuum would exist in the vessel. But since water would not run out of a vessel unless air entered, the problem was how to get it out. Otto von Guericke of Magdeburg (1602-1686) began with the idea that if he had a barrel filled with water he could get it out with a pump attached at the bottom. He did—but the barrel collapsed. With a stronger cask, three men were able to get the water out successfully, but then air poured through the tightest joints and filled the vacuum. Next he used a large hollow globe of copper, and attempted to pump out the air directly, without first filling with water. After several attempts he thus succeeded in producing a high degree of vacuum, and was able to exhibit publicly the astonishing pressure with the aid of his "Magdeburg hemispheres" and other devices.

Von Guericke's work was epoch-making. Perhaps nothing was more astonishing than the fact that a vessel when emptied of air weighed appreciably less than before the air was removed, which showed that *air had weight!* Not only so, he showed that the vessel full of cold air was heavier than if it were filled with heated air!

Robert Boyle's experiments with the pressure of air were published in 1660, a little earlier than the announcement of Guericke's work.

In 1643 Torricelli had obtained a vacuum in the upper end of a glass tube by filling it with mercury

and then inverting it in a cistern of that liquid. The mercury stood at a height of only thirty inches, no matter how long the tube was. Following this came a time of almost feverish interest, until the so-called barometric column of mercury was shown to be due to the weight of the atmosphere, or was sustained by atmospheric pressure.

AIR UNDER PRESSURE USED TO DISPLACE OTHER MATERIAL—CAISSON WORK

The progress of chemistry revealed other gases, and the properties of gases as such were a fruitful subject of investigation. Eventually this led to what we now call the kinetic theory of matter, in which, in connection with the laws of motion, it is shown that the pressure of a gas is due to the multitudinous impacts of the particles of the gas against the walls of the vessel containing it.

The buoyant effort of a liquid upon a solid that is placed in it, so great in many cases as to make the solid float, is the essence of the noted Principle of Archimedes, and, as we now know, applies to gases as well as to liquids. An interesting corollary to it is the use of gas to displace a liquid. When it was learned that a gas, like a liquid, could be pumped out of a vessel, it immediately became evident that it could likewise be pumped in.

To-day no considerable engineering work is performed without the use of compressed air, and many large and deep foundations are built upon submerged caissons placed by its aid. The caisson is a huge, strong, inverted box, open downward, placed in the water where the pier is to be erected. It is built upon, and thus heavily weighted. By means of a pipe to the interior, air is forced into the

chamber with sufficient pressure to drive out the water and keep it excluded, while men within the chamber excavate the ground in the middle and around the edges, and the caisson is gradually sunk to a solid stratum of earth or rock.

Such an atmosphere presents peculiar conditions of living. Aside from the effect of pressure, a surfeit of air may entail conditions as unpleasant and as dangerous as a deficiency. Moderate bodily exertion here is sufficient to heat one excessively, for under four times the normal pressure, one inhalation takes into the lungs four times as much oxygen as at the surface of the earth, and the burning of the tissues is correspondingly rapid. So exhausting is work under this high pressure that it is kept up only one hour and then one set of men gives place to another. A shift of one hour for the same men later completes their day's work, which thus consists of two hours' actual labor. Hot and close as it is here, the ventilation is good. Air leaks out all around the edge of the caisson and may be seen boiling up at the surface of the water outside. More than enough air is supplied from the compressors to renew the entire contents of the caisson chamber every hour. The place is well enough lighted by incandescent electric lamps, and candles are at hand for inspecting obscure places. These burning candles furnish another illustration of the effect of the dense atmosphere. You cannot blow them out. If the flame is blown from the wick the latter remains momentarily aglow, and so abundant is the oxygen in the air that it immediately rekindles the flame and the candle blazes as before.

With the first remark the visitor utters he is startled by the strange sound of his voice, and his

singular enunciation. He does not recognize his own voice, and looks around to see if some one was uttering his thoughts for him. The articulation becomes very indistinct, as if the excessive density of the air made it slow to respond to the vocal organs; f's and t's are scarcely heard, or change strangely into l's. The tone also is altered, taking on a peculiar character of lightness and flatness. One cannot whistle in a caisson chamber; try as he will, the whistler's efforts are of no avail, absolutely no sound proceeds from his lips!

It is passing from the denser to the rarer atmosphere that is likely to produce physical injury if any is to ensue. Sometimes the effects show themselves in severe pains in the limbs, in more dangerous cases the pain attacks the chest and paralysis ensues, which may result in death. So it is more important that the change of pressure be accomplished slowly in coming out of the caisson than in going into it.

CHAPTER V

FORCE AND MASS

THE TWOFOLD CHARACTER OF FORCE

SINCE mechanics deals with the action of bodies when force is applied to them, we need first of all a clear idea of mass and force. There are only two ways in which force could be estimated, outside of one's own effort: one, by the effort which a body makes to regain its original form after it has been distorted, or by the resistance which it offers to further distortion, giving a static measure of force; and the other, by change of motion in bodies, giving a kinetic measure.

Before examining the effect of force in detail we should take note of something in regard to it that is frequently overlooked. When the "untutored" Indian places the blade of his paddle in the water, and bracing himself in the canoe, vigorously pushes the paddle backward, the less the water gives way the more the canoe is propelled. Which, then, has he really pushed with the paddle, the water or the canoe? The Indian surely does not bother his mind about any "laws of motion" or any formula of "action and reaction," but it is vitally important to physics for us to recognize that the exertion of any force always concerns two bodies, or we can view the force under two aspects. If we fix our attention upon one of the bodies, we say the force is applied to, or acts upon,

that body, but we can just as truly regard the force as exerted upon the other body, oppositely and equally, and that is called reaction. This truth Newton stated as a law of motion.

We see that the thrust of the paddle backward pushes the canoe forward. If the paddle had been moved crosswise to the course of the boat, but with its face inclined at an angle to its own direction of motion, a part of the reaction of the water against it would have been effective in the line of the boat and would have gone to push the boat ahead. Now mount a number of paddles like spokes of a wheel on a longitudinal shaft, say at the stern of the boat, with the face of the blades at an angle to the axis of the boat, and you have a "propeller," which, in rotation, makes a push that is practically continuous, instead of the intermittent stroke of a single paddle. In place of the canoeist to manipulate the paddle put an engine to drive the propeller shaft, and you have the mechanism of the leviathan of ocean travel, crossing the Atlantic in less than five days, and transporting a cargo of thousands of tons. If the blades upon the shaft are in front of the vehicle to which they are attached, they will pull instead of push it and the machine becomes a "tractor," such as is used on an airplane.

WHAT IS MEANT BY MASS

No science was needed to teach that bodies differ in weight—that it required a greater effort to lift some bodies than others; that is a fact that could not escape observation, though it was long before weight could be accounted for. That a small piece of copper should weigh more than a larger piece of wood, and at the same time less than a smaller piece

of lead, seemed inexplicable. The answer was found in the structure of matter; some substances have more actual matter in a given bulk than others. A piece of lead and one of wood of the same size have not the same amount of material. The actual amount of material in a body is termed its *mass*. But, after this conception had been formed, still it was not known whether the weight of different bodies varied in just the same proportion as the amount of matter in them. This problem—whether different bodies have different masses—was not solved until the time of Galileo, when dynamics (the science of forces) was definitely connected with the effect which force had upon the motion of bodies.

When a force is applied to a body, either the position of the body as a whole is changed or its shape is changed; i. e., the position of one part relatively to another part is altered. The first of these is an illustration of inertia, which we have already mentioned; the second is immediately connected with another special feature of matter.

ELASTICITY

Among many properties which different kinds of matter possess in different degrees, such as hardness, brittleness, ductility, etc., there is one that characterizes all bodies, and has an important part in a wide range of phenomena. If a body is pressed, or bent, or stretched, or twisted, a force is needed to keep it so distorted, and if its distortion has not exceeded certain limits, when the force producing the distortion is relaxed, it springs back to its original form. With some bodies a small force will produce a considerable change of form or size; with others a large force produces only a small change. This

property of matter by which a body endeavors to regain its form is called "elasticity." Ivory, steel, india-rubber, are highly elastic; clay is scarcely so at all. But there are no substances that are wholly lacking in elasticity. One of the earliest forms of weapon was the bow and arrow, and the efficacy of the bow is entirely owing to its elasticity. In higher physics, next to inertia, elasticity plays probably the most important rôle. Especially is this the case in connection with gases, and heat, and in many of the phenomena of vibration and sound.

CHAPTER VI

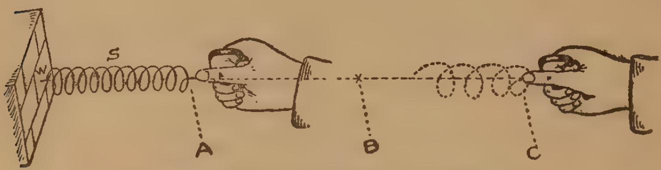
WORK AND THE TRANSFERENCE OF ENERGY

IN common conversation "work" does not always mean the same thing, nor does "energy," but there is nothing loose or vague in the scientific use of these terms. If a man lifts a weight of twenty pounds from the floor, he is doing work while he is raising the weight; but if he holds it steadily at a fixed height all day long he will, technically, be doing no work on the weight, though when evening comes he will be exhausted, and no assurances of physics will convince him that he has not done a hard day's work—on himself. Work and energy are directly exchangeable in value; work done to a body confers energy upon it; energy expended does work—i. e., transfers energy to some other body, and such a process of exchange is illustrated mechanically thus:

If S is an elastic spring with its end W fixed, and the hand begins to pull upon the other end at A, the spring is gradually drawn out. A slight force will elongate the spring a little; then more force is required to stretch it further. By the time the hook has reached B, a considerable force will have acted in moving the hook in the line of action of the force; and by still adding to the force the spring may be extended, say, to C.

The spring is now in a very different condition from that at the beginning, and work has been

expended upon it, represented by the force that was applied, and the extent of movement in the direction of the force. In this case the force was in the direction AC, but was steadily increasing in amount. Some aggregate amount of work was done on the spring, and the spring now is capable of doing work which it could not do before. That capability is energy which the spring has acquired in virtue of the work done upon it. If, now, the effort of the



INTERCHANGE OF WORK AND ENERGY

hand at C is in the least relaxed, the hand is drawn back by the spring toward A, and, with a continued lessening of the pull by the hand, the latter is continually drawn along by the force of the spring until it finally brings the hook back to A. But in this case the spring has done just as much work upon the hand as the hand had before done upon the spring, for it has exerted exactly the same force to move the hand through the same successive distances, in the reverse order, and in doing so it has exactly given up the energy it had acquired from the work done upon it.

Whenever, in consequence of the application of a force to a body, it is changed in position, or shape, or rate of motion, work is said to have been done upon the body, and in getting back to its original condition the body can move or change other bodies, by means of the energy it has acquired; the work

may have been mechanical, but the energy acquired may be returned either in a mechanical form or some other form, such as that of heat or of an electrical current. But the work on A has been done by some other body B; and however it is done, the doing of it is, in effect, a transferring of energy from one body to another; and the energy thus transferred is an added capability of the other body to do work. All the phenomena of physics are transferences and transformations of energy, and these phenomena are manifested in various guises of mechanics, sound, light, heat, electricity and magnetism, and will be considered under these heads separately.

We are not, however, any longer to think of these various manifestations as independent and unrelated experiences of nature, although it is of comparatively recent date, only since about 1840, that the phenomena of these various classes have been correlated in one scheme of energy, unless it has been expended in effecting some changes within the body. Until that time, while a resemblance could be traced between sound, light, and heat, their phenomena were necessarily considered as if they had no underlying principles in common, and so were detached subjects of science. It is the triumph of modern science to have discovered and identified this common principle.

In this case we are now considering when the hand and spring have returned to their initial position, there is nothing accomplished, yet the possessor of the hand will feel the effect of his exertion, because of chemical or biological changes within his system. So too, with the man who was holding the weight suspended: so far as the unmoved weight is con-

cerned, no work was done upon it, nor was its energy altered so long as it was not moved.

CONSERVATION OF ENERGY

The great principle which has unified modern physics is the conservation of energy. That means that energy cannot be created or destroyed. The doctrine as applied to matter includes two ideas:

"All kinds of energy are so related to one another that energy of any kind can be changed into energy of any other kind." This is the correlation of energy.

"When one form of energy disappears, an exact equivalent of other form, or forms, always takes its place, so that the sum total of energy is unchanged." This is the conservation of energy. It must be understood, however, that its application is limited to the bodies constituting one definite set. The total amount of energy in any body or system of bodies is constant, unless the system is acted upon by forces from without. In such case a gain of energy is at the expense of some other system producing the change, by an exactly equal amount, and so we reach the conclusion that the total energy in the universe is an unchanging and unchangeable quantity.

"Work is a transference of energy from one system to another; the system which gives out energy is said to do work on the system which receives it, and the amount of energy given out by the first system is always exactly equal to that received by the second. If, therefore, we include both systems in one larger system, the energy of the total system is neither increased nor diminished by the action of one partial system on the other." The doctrine of the conservation of energy has been pronounced to

be "the one generalized statement which is found to be consistent with fact, not in one physical science, but in all." So completely does it envelop all physical phenomena, and so satisfactorily does it account for them and show their relationship to one another, that if any statement is made or any theory of action is propounded at variance with this doctrine it is discredited on that account. Now and then a new discovery seems to set the doctrine aside, but supposed contradictions have, so far, always given way in the light of further investigation.

DIFFERENCE BETWEEN ENERGY AND FORCE

Energy or work should not be confounded with Force. Force is simply an effort exerted by or upon bodies at any instant. It may be increased or decreased, multiplied or divided, created or destroyed, at the will of the operator.

In a hydraulic press, if the large plunger has an area a hundred times that of the small piston, a force of one pound applied to the latter will produce a pressure of one hundred pounds by the former. If one arm of a lever is twenty times as long as the other, a force of five pounds at the end of the long arm will cause a lifting effort of one hundred pounds at the end of the short arm, and the withdrawal of the applied five pounds will not only cancel an equal five pounds at the other end of the lever, but an additional ninety-five pounds will vanish. Nothing like this occurs with energy. No body gains or acquires any energy without some other body losing an exactly equal amount.

CHAPTER VII

GREAT ACHIEVEMENTS THE DEVELOPMENT OF APPARENTLY TRIVIAL ACTIONS OF NATURE

EVERYBODY has witnessed the unsteady action of a falling leaf or fragment of paper. With a little slant from its position, it sheers off, exposing a larger surface against the air beneath it, and thus more fully supported, it may dart to one side at a rate that will even make it rise somewhat; with another change of position its upward movement is checked and it falls again, and in this erratic fashion it finally reaches the ground, far from the spot on which it would have alighted if it had fallen vertically. It was the action of gravity that made it fall. If it had been tossed away laterally instead of vertically, how would it have gone? Gravity would still bring it to the earth, but it would probably undergo some peculiar movements on account of its lateral propulsion. Savages long ago learned that a thin blade of wood may be so shaped that when thrown at a slight inclination, as it whirls, the air pressure will cause it to take a curved course, by which it will return to the thrower, and thus he produces the boomerang.

The civilized boy (and man) spreads the sheet of paper or linen on a light frame, attaches a pendant or tail to steady it, and a string to hold the face of the contrivance against the wind, and he has the

kite, which rises and is held aloft by the upward effort of the wind blowing against the inclined surface. Then it is found that a better effect can be got by arranging the surface in an open box shape through which the wind blows.

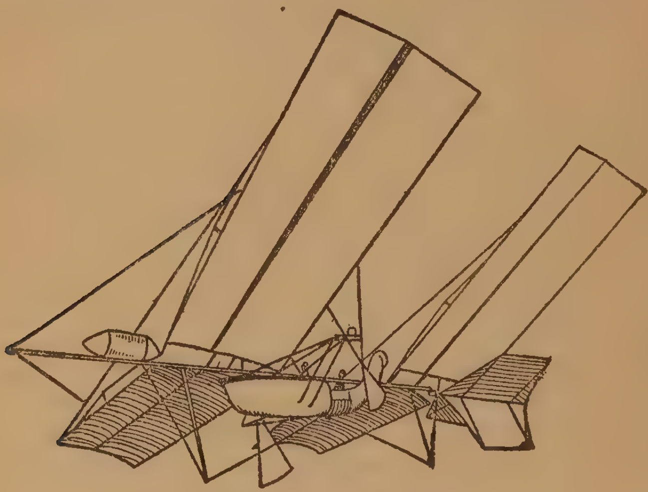
Whether the wind blows against the surface, or the kite is drawn against the quiet air, the pressure is the same, and if sufficient speed is given to the apparatus enough pressure may be obtained to lift it. A fine, strong fabric is securely spread upon a light metal frame, which also carries a propeller and an engine that drives the propeller at a high speed; this gives to the apparatus a forward motion that may be brought to such a high velocity as to lift it and carry it onward rapidly, and we have the modern triumph, the airplane, crossing the Atlantic in *fewer hours than days required by Columbus.*

In this marvel of applied physics, to the scientific observer perhaps the moment of most intense interest is that of "taking off," when, driven along the ground by the propeller, the speed has increased until the critical instant at which the upward reaction of the air against the surface of the planes just equals the weight of the machine, which now leaves the earth, rises gracefully, and sails away with its ever-increasing speed.

Much of the really scientific investigation that preceded the practical evolution of the airplane was done by the late Professor S. P. Langley, who determined by extended and ingenious experiments how much lifting effort is exerted by a square foot of surface at various inclinations and various speeds.

While conceding the utmost merit to the inventors who so rapidly and successfully developed the air-

plane, the physicist cannot, and others should not, fail to recognize the great work of Professor Langley as a pioneer in aeronautics. His critics condemned him for wasting time and money upon a toy. In 1896 he wrote: "I have had only a purely scientific interest in the results. . . . I have brought to

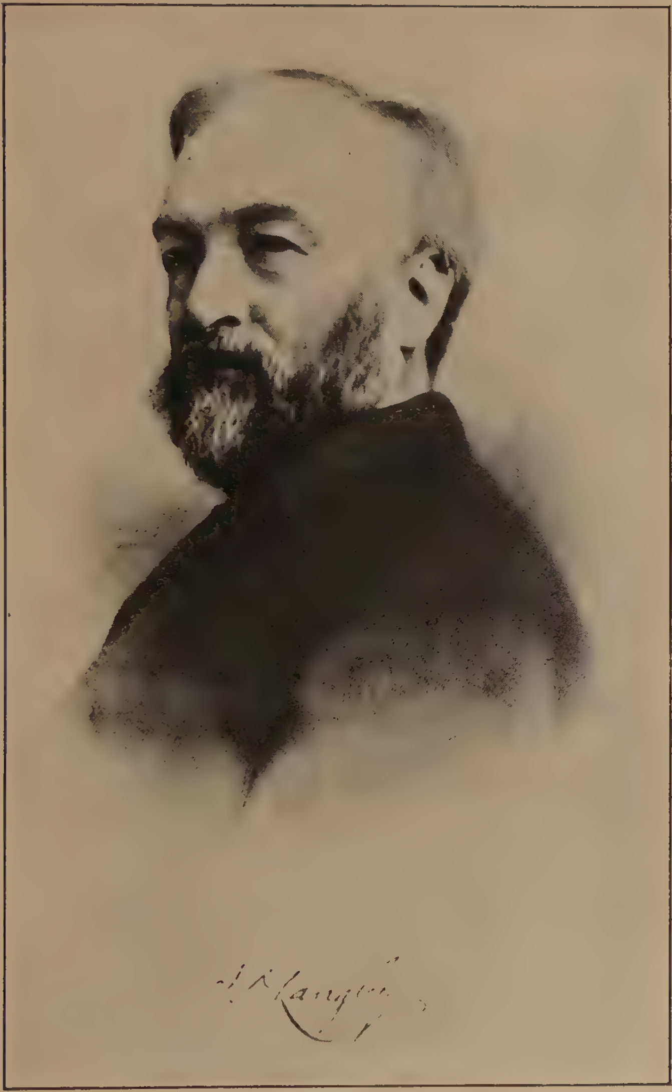


THE LANGLEY AERODROME MODEL

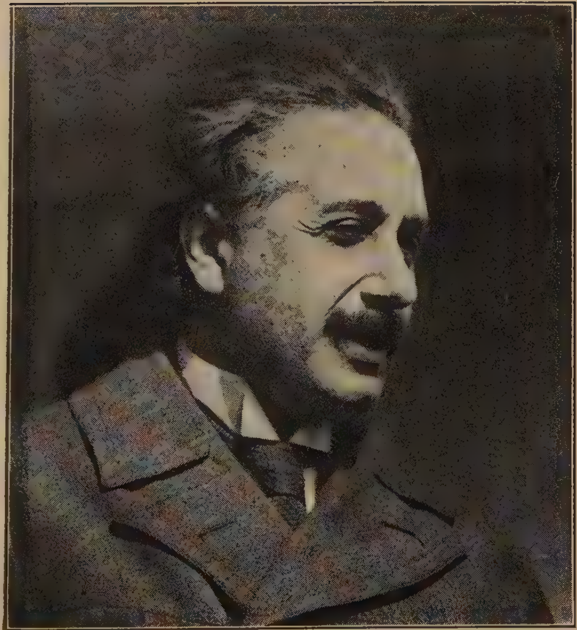
As it made a flight of more than half a mile in one minute and a half, above the Potomac River, May 6, 1896. It was driven by a steam engine, which, with its boiler, weighed less than seven pounds.

a close the portion of the work which seemed to be specially mine—the demonstration of the practicability of mechanical flight—and for the next stage, which is the commercial and practical development of the idea, it is probable that the world may look to others."

In the glorification of the "practical" inventor, the debt of the world to pure science was long disregarded, but in recent times large organizations



SAMUEL PIERPONT LANGLEY



ALBERT EINSTEIN

NIKOLA TESLA

have found it profitable to maintain laboratories, conducted by skilled scientific men, exclusively for research *preliminary* to commercial development.

SCIENTIFIC DEFINITENESS DEMANDS MEASURES AND UNITS

We cannot compare quantities without using measures of some kind. We may speak of an object as very large, but if we want to say just how large, we give its size in feet or inches, or compare it with some other body as a standard; we may say it moves very fast, but if we want to tell how fast we speak of so many feet per second or miles per hour; if we want to buy or sell produce we measure the amount of it as so many pounds or tons. Now, no matter what it is that is to be estimated, in physics everything is sized up in terms or, as is said technically, measured in dimensions of length, mass, and time. Some definite amount of matter must be recognized as a unit to measure mass, and some definite length as a unit of distance, and some period of duration to measure time. The last, we have already seen, is the year for long periods of time and the second for short periods.

Great Britain and the United States have adopted by legal enactment a standard bar whose length is a yard (the yard was supposed originally to represent the reach of an arm's length by the English King Henry I; and to-day the housewife may be seen checking off the merchant's measure of a piece of dry goods by holding the edge at her nose by a thumb and forefinger, and extending the piece as far as she can reach with the other thumb and forefinger). One-third part of this length is a foot, and one thirty-sixth part an inch; similarly a piece

of platinum of fixed size has been adopted as the standard of mass and is called a pound.

Other nations use other quantities as the basis of their measurements. Throughout the civilized world, however, there are only two systems of measuring now in general use: one, the British, just described, and called the foot-pound-second (f. p. s.) system of units; the other, with a meter (somewhat longer than the yard) as the standard of length, subdivided into one hundred equal parts called centimeters; and for mass a lump of platinum more than twice as large as the pound, called a kilogram, of which the one-thousandth part is the small unit called a gram. The whole set of measures in these units is called the metric or centimeter-gram-second (c. g. s.) system.

Magnitudes or quantities which do not seem to be masses or lengths or times can all be reduced to them ultimately, and though we have separate units for them, those units are themselves determined by their length or mass or time. For instance, a body of liquid may be very wide and shallow, or very narrow and deep, and so it would not be expressed as so many feet or inches, but as so many gallons, yet the gallon measure itself is simply a vessel of any shape whose volume is 231 cubic inches. So the unit of length is sufficient for measuring gallons. Secondary units like the gallon are all derived from the primary ones of length, mass and time. The first and most important derived unit is that for measuring force.

CHAPTER VIII

FORMS OF ENERGY

MECHANICAL RELATIONS OF HEAT—"THE IMPONDERABLES"

TWO of the great branches of physics are concerned with heat and light. The early physicists spoke of these as "imponderables," because they could not be weighed. To account for the phenomena of heat and light, they imagined an imponderable substance composed of minutest particles, which was supposed to be taken in or given out by bodies; this substance when it produced the effects of heat was called "caloric." This theory of the nature of heat was first seriously shaken by the work of a native American, Benjamin Thompson (1753-1814), now more generally known as Count Rumford. Great additions to scientific knowledge were due to Newton. He maintained the corpuscular theory of light, and in consequence of his powerful support, this theory was not completely displaced by the undulatory or wave theory until the early part of the nineteenth century.

Up to the time of Count Rumford, the best that scientists could do with heat in theory was to regard it as a substance which they termed "caloric," which bodies could take in or give out according to their "capacity," or which, in a normal state they could retain and under certain conditions could liberate to a limited extent. In 1803-1804, Rumford

showed by special experiments made in connection with the boring of cannon, that the mere fact of friction would produce apparently an inexhaustible supply of heat from a small mass of metal. A little later his experiments were supplemented and his conclusions substantiated by Sir Humphry Davy. In a famous experiment, this philosopher showed that ice, in an atmosphere colder than freezing, could be melted simply by rubbing two pieces of it together vigorously; thus was opened the way to connect the evolution of heat directly with mechanical work. Not only were old notions overthrown, but a good beginning was made toward establishing the modern (dynamical) theory of heat. Indeed, as Rumford had used horses to operate his boring machine, he had the keenness to observe that the heat which he could get depended upon "the fodder necessary for the support of a horse as fuel." This was a very early foreshadowing of the modern practice of rating food values in "calories."

The facts in human experience upon which Rumford and Davy proceeded were not new. It was known from prehistoric times that friction or hammering would make a body hot. Only now it was seen that this resulted from concentrating much effort upon a small portion of matter. Savages and men in a primitive state had learned long before that a fire could be produced by rubbing together two dry sticks of wood.

Then came the still more violent concentration of energy upon a minute particle by striking flint with steel, and sparks were produced to kindle a flame in tinder. Under the abrasion of a rapidly revolving grindstone, fragments are torn from a blade of steel,

with the generation of so much heat that they become incandescent and fly off in a scintillating shower. Few of us appreciate the fact that the friction match is a comparatively recent production. The progress of science in the last fifty years has been so rapid that anything of an earlier date seems ancient. In the days when the blacksmith's shop was a more common institution in rural communities than it is now; when the shoeing of horses was a large part of the smith's work, and when he made his own nails for the purpose by forging them one by one from the end of a slender iron rod, it was the boast of the expert smith that he could hammer so hard and fast that the iron would soften with heat and so could be forged without his putting it into the fire.

It was in following the new trend given to the physics of heat that Dr. James Prescott Joule of Manchester, England, between 1842 and 1847 showed that a body would become hotter by a mere increase in the agitation of its molecules.

His original apparatus was a vessel of water in which a dasher carrying vanes that were perforated with numerous holes was rotated, and thus the water was stirred. The stirring of the water was the only means applied to heat it. The rotation of the stirrer was effected by the descent of weights and the work so expended was compared directly with the heating of the water. By 1847 his determinations were sufficiently verified for him to announce that the work of 772 foot-pounds would raise the temperature of one pound of water one Fahrenheit degree. This was an accepted standard value for nearly thirty years. Then (1879) Professor Henry A. Rowland of Baltimore, Md., redetermined this

important relationship to resolve doubts that had been raised by the British Association for the Advancement of Science, and found for a mean value 778 foot-pounds.

Dr. Joule further showed the relation of heat produced by mechanical work to that resulting from the passage of electric currents, and also from chemical action, and thus, about 1850, were laid the foundations of modern physics as a science of energy.

GREAT ADVANCES IN THE APPLICATION OF LIGHT

Since each branch of physics plays a distinct rôle in the drama of civilization, it has to some extent a character of its own. If we may call Mechanics the artisan, Heat the engineer, Electricity the messenger and general utility man, and Sound the musician, we may fairly regard Light as the gentleman and perhaps the artist in physics: not that the gentlemanliness in the least detracts from its usefulness, but he has nothing to do with grease or grime.

In some respects the theory of light may almost be said to have gone backward, for the discovery of various Crookes tube phenomena and of radioactivity has revealed many instances of radiant energy, which once might have been classed with light, but which are to be explained only by a corpuscular theory, and the field of light is correspondingly limited.

While light has made no very striking advances lately in theory, its application to convenience and comfort in living—the art of lighting—has made great strides.

The possibilities of this kind that have resulted from the advances in applications of electricity have

cheapened and made available the most varied, effective, and extravagant use of light for every conceivable purpose. Artificial daylight is introduced into dingy factories and workrooms; violet and ultraviolet light is used in medicine and sanitation, and colors in the greatest variety and profusion, arranged with great ingenuity, are employed for signs and purposes of display; and *Illuminating Engineering* has become a profession as distinctly specialized as civil, mechanical, or electrical engineering.

We can hardly conceive of the discomfort and disadvantages under which many young people and practically everybody past fifty years of age, must have lived in former times with no means to relieve defective or failing eyesight, and with only candles, torches, or other ineffectual illuminants to take the place of sunlight, and mitigate the dreariness and dangers of darkness. We know it would be appalling if we were to-day to be deprived at once of our magnificent means of artificial lighting, and of eyeglasses that may be adapted to every defect of vision. The horrors of a world of darkness could be equaled only by those of a world of silence, and the privations of semi-blindness would make many an otherwise happy and useful person a burden to himself and to society. For this part of civilization, the application of scientific principles to the arts of lighting and of making optical instruments, we are indebted mainly if not altogether to physics.

THE THEORY OF SOUND

Not least among the refinements of civilization is the "concord of sweet sounds." Not all sounds are pleasant, but they are productive of every sort of

thrill—the scream of terror, the cry of fear or pain, the pathetic dirge, the stirring strains of martial music—sounds in one or another mode of utterance awaken a response throughout the entire gamut of emotions. The earliest branch of physics to have its phenomena ascribed to wave motion was that of sound. The explanations of sound have been challenged and the very fact of the existence of sound waves has been disputed, but the theory has vindicated itself by the completeness with which it has met all difficulties. In the majority of instances sounds are of a complex character, but later on we shall see that these are at bottom combinations of simple sounds.

Helmholtz's remarkable work in analyzing complex sounds and then synthesizing them, reproducing tones of various qualities by combining simple sounds of known character, supported and followed by the mechanical and scientific skill of the acoustician Koenig in Paris, went far to place the theory of sound on a secure basis. Lord Rayleigh demonstrated that diffraction applies to sound waves as well as to light, if only sufficiently short waves can be produced and controlled. In later days the actions of sound waves have been visualized by photographing them in their actual formation and progress.

THE PROGRESS OF MAGNETISM AND ELECTRICITY

The lodestone, with its peculiar quality of pointing toward the pole, is said to have been known to the Chinese for ages, but magnetism and, later, electricity, as branches of physical science, date from less than three centuries ago. The lodestone was the guide by which Columbus steered until he discovered that it was playing him false. He had at last cut

loose from the bonds of doubt and opposition at home, and then, after he had set out upon the last stage of his voyage, the success of his expedition was imperiled and his hopes were again jeopardized by the discovery that the compass needle no longer pointed to the same spot in the heavens. He was hard put to it to allay the alarm of his sailors, and to account for this failure of the needle, which he himself did not understand; but his cleverness was equal to formulating a plausible reason which tided them over the immediate danger.

That about represents the status of magnetism and electricity in England in 1667. In his Diary for May 30 of that year, Samuel Pepys speaks of a visit by the Duchess of Newcastle to the Royal Society and says: "She was full of admiration, all admiration. Several fine experiments were shown her of . . . . lodestones, microscopes, etc." Mr. Pepys was not much of a scientist, but there was little of importance that escaped his notice, and if any phase of science had much of promise in it, he would not be likely to speak of it slightingly. In Dr. Thomas Birch's History of the Royal Society, the secretary speaks of this visit of the Duchess of Newcastle, and enumerates the experiments appointed for her entertainment, including "First, that of weighing the air, . . . next, several experiments of mixing colors. Then, two cold liquids by mixture made hot"; and three others, but makes no mention of any magnetic experiments: which indicates that such would be of even less interest and significance than the preceding ones. The performances of the lodestone, therefore, would seem to have been merely injected casually into the program for her entertainment.

It is a chain of many links, stretching from that to the electromagnetic engine and the wireless service of to-day; from toying with bits of amber or lodestone for the entertainment of a lady of fashion, to the flashing of messages half round the world and other achievements that surpass the greatest feats of magic and transcend the powers of the genie summoned by Aladdin's lamp.

At the World's Fair in Vienna, in 1873, the electric dynamo, then in its infancy, was on exhibition. An assistant, desiring to unite one which was idle with one that was running, to increase the output, connected the terminals, expecting to apply additional power to the second dynamo. On making the connection he was astonished to see the second machine start up and run as a motor. The startling discovery was made! The dynamo and the motor were interchangeable—either one could be driven by power to generate current, or be driven by an electric current to generate mechanical power; a discovery which the distinguished physicist, Professor James Clerk-Maxwell, pronounced the greatest that was made within a quarter of a century.

It was only three years after this, in 1876, that Professor Maxwell produced his great work on Electricity, giving true scientific character to the Faraday conception of fields of force and lines of force; and pointing out that the propagation of electric influence through space was so like that of light and so general in character, that light itself ought to be treated as an electromagnetic phenomenon. Just about this time (1878), Sir William Crookes exhibited his extraordinary work on the electric discharge through highly rarefied gases, which led him to treat that condition of a gas as "radiant matter"

or a "fourth state of aggregation"—an ultragaseous form, supplementary to the solid, liquid, and gaseous states. It is among the most remarkable of "Fate's ironies" that the former of these two great physicists just did not actually identify electric waves in space; or the latter radioactivity; both of which discoveries were soon to follow, and be developed with a rapidity that has left all but specialists gasping.

In December, 1895, Professor Wilhelm Roentgen, of Würzburg, first made public his discovery of X-rays, and only in early 1896 did news of it reach America. Even then the first reports of it were far from clear, and were received with general incredulity; but its startling character stimulated physicists everywhere, amateur and professional, and out of confused results gradually came more accurate acquaintance with the phenomena of cathode rays as well as those from the anode. The human hand was the favorite and most convenient object for testing the penetrating effect of the X-rays, as also their photographic action, the pictures fascinating by their weirdness.

As if all this were not marvelous enough, Professor J. J. Thomson of Cambridge, England, succeeding Maxwell, and following up Crookes's and Roentgen's experiments, invests the atom with a complex structure of positive and negative ions, which leads to a readjustment of views concerning the very nature of matter itself as well as its phenomena.

PART II

ELEMENTS OF PHYSICS

CHAPTER IX

FORCE AND MOTION—VELOCITY AND ACCELERATION

THE elementary principles in the relation of force to the motion of bodies are not hard to grasp, and we can afford to devote a few pages to them, for without them it is impossible to acquire more than a superficial knowledge of the subject. A body in motion may be going faster or slower in some cases than in others; a fact which we express by saying its speed is different. If it does not change the direction in which it is traveling, its rate of travel is called its velocity. It is measured by the distance traversed in a given time and is expressed by the distance in a unit of time, as, for instance, feet per second or miles per hour. If it travels one hundred miles in four hours, that is *at the rate* of twenty-five miles per hour, which is its speed or velocity, but it need not go a hundred miles, or twenty-five miles, to have that velocity. If its motion lasted only one twenty-fifth of an hour, but in that time it traveled one mile, it would be at the rate of twenty-five miles per hour, and that would be its velocity. We even speak of the velocity which a body has *at any instant,*

by which we mean the distance it would go in a unit of time, say the number of feet in a second, if it kept on going for a second without change, as it was going at that instant. Any distance traveled, divided by the time required, will give the average velocity during that time.

If a body does not travel at a uniform rate, the change in its velocity is called acceleration, accounted positive if the motion becomes more rapid, negative if it becomes slower. The acceleration is measured by the velocity that is added to or taken from the velocity which the body already has. If the latter starts from rest, any velocity which it acquires is acceleration. If it starts from rest, and after five seconds has a velocity of 100 feet per second, that is its total acceleration; but we more commonly say it underwent an increase in velocity of 20 feet per second, every second, which, in five seconds, would give it a velocity of 100 feet per second; or, it received an acceleration of 20 feet per second, per second. That last "per" is sometimes confusing, and might be substituted by the word "every" or the words "in a." It takes both distance and time, as feet and seconds, to express velocity; we cannot speak of a velocity of so many feet or so many seconds, but of so many feet per second; and then, as acceleration is change of velocity in a second, it becomes feet per second, in a second. But keep in mind, that the acceleration is not always the velocity to which the body has attained, but the rate at which the velocity was changed. A constant acceleration will produce in the body a constantly changing velocity, increasing or decreasing. Unless otherwise stated, we generally treat acceleration as increasing the velocity.

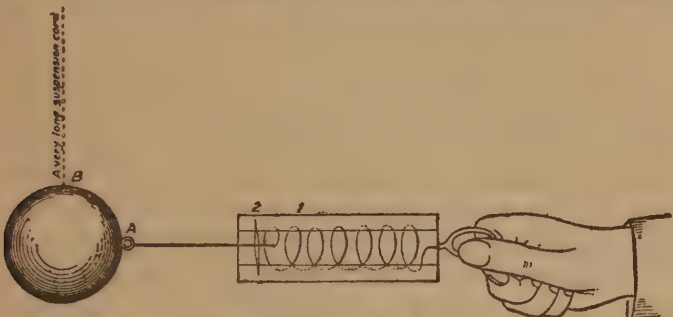
FORCE AND MOTION

The effort required to lift a body from the earth is a force that just matches the force with which the body is held to the earth. This is known as the weight of the body, and is attributed to the action of "gravitation." That is something that we have to consider later. The weight of bodies served as a convenient measure of force, before the relation of a force to the motion it could give to a body was understood, and this led to an unfortunate confusion of terms, for the weight of a pound mass was called a pound force, and forces as well as masses came to be counted in pounds, though a pound mass is not at all the same thing as a pound force—and cannot be, since mass and force are themselves two totally different things. It is much the same as if we should speak of distances by miles and also by hours. A mile and an hour might be associated with each other in a perfectly definite relation, but they would not be the same thing. Still, the term pound is now used in both senses, and to serve both purposes. If one pound is suspended from a spring, and the end of the coiled spring is thereby drawn down to a point marked 1, that will mark the extension of the spring by a force of one pound; if two pounds are suspended and the pointer at the end of the spring is drawn down to a point marked 2, that marks a force of two pounds, and in that manner a spring balance may be made to indicate various forces.

Now forget all about gravity and weight. The same force will be required to extend the spring to one, two, three, etc., if it is attached to a post, and stretched by pulling upon it horizontally, for it is

not to be supposed that the spring knows anything about horizontal or vertical position.

Suppose B is a piece of platinum five times as great as the standard pound, and therefore having a *mass* of five pounds, so placed as to be free to move only horizontally, in which direction *weight* does not act. B might be considered suspended by a *very long* fine thread, so that with considerable horizontal movement it is not sensibly raised. Then, for horizontal action it would be virtually as if



FORCE, MASS, AND MOTION

poised in mid-air. The spring balance is attached as in the figure and pulled steadily with the pointer continually at one. The body moves faster and faster, until, at the end of a second, it has gone over a distance of 3.2 feet, and if the hook A is then detached, B moves on uniformly, going 6.4 feet in the next second. It started from rest, i. e., with no velocity, and under the influence of a force of one pound, it *gained* a velocity of 6.4 feet per second. This gain of velocity is its acceleration, and as long as the same force is kept pulling at B, the body goes on gaining this additional velocity every second. This gain of velocity is its acceleration, said to be 6.4 feet per second, per second.

Starting again as before, but maintaining a pull of two pounds, B is moved twice as far in a second, and in that second has acquired a velocity of 12.8 feet per second. With a force of three pounds the acceleration is three times as great as with one pound. If B is in motion at a known rate when the pull of one pound at A begins, then, after the pulling has been kept up for one second, B will be moving with its original velocity *plus* the increase of 6.4 feet per second. The effect of the force is to *change the velocity*, or to cause an acceleration.

No matter how much or how little force is applied to B, its change of velocity per second is in proportion to the force that is applied. On the other hand the actual change that will be produced by any force, say one pound, will depend upon the mass of the body B. If we use any fixed force, one or two, or any number of pounds, and find the acceleration it would give to B if B had a mass of one pound, then if we replace it by a mass of two pounds, the same force will give it just half the acceleration; if the mass is made ten pounds, the force will give it an acceleration one-tenth as great as it gives to a mass of one pound. In such case the acceleration is said to be inversely proportional to the mass.

We now have the general statement that when a force is applied to a body that is perfectly free to obey the force, the body undergoes an acceleration that is directly proportional to the force that is applied, and inversely proportional to the mass of the body.

This statement may be rearranged in its terms, to express the same facts, thus: when *a certain acceleration* of different bodies is effected by different forces, the forces will vary just as the mass of the

bodies varies; and when a given body receives different accelerations, the forces producing the accelerations will vary just as the acceleration does.

These results, simple as they are, were arrived at only after long and patient experimenting by Galileo. He had no such definite ideas of mass, time and force, from which to proceed as we have represented here, and his investigations were directed primarily to the motion of bodies falling to the earth from a height, or descending along an inclined plane.

NEWTON'S LAWS OF MOTION

The conclusions to be drawn from the work of Galileo, as well as from that of his predecessors, were stated concisely by Newton in his so-called laws of motion, with a completeness and definiteness that has made them the basis of mechanics from that day to this, although Newton used some phrases for which we now employ somewhat different terms to express his meaning.

The three laws, as he gave them in his great work, "The Principia," are as follows:

1. Every body perseveres in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by forces impressed thereon.

The body is supposed to be perfectly free from the resistance of the air or anything else; then if it is at rest, it will remain so; and if it is in motion, it will continue to move on in a straight line, at the same speed; unless, in either case, some influence from without itself, acts upon it to change its motion. It has no power within itself to change its state either of rest or of motion. This is often called the law of inertia. It merely declares the existence

of inertia, but says nothing about the amount of force required to overcome the inertia.

Inertia of bodies is so constantly in evidence that we pay little attention to it. If a car is started forward suddenly, a passenger in it is jerked backward; if it stops suddenly he plunges forward. A striking example is the way in which a bicyclist maintains his equilibrium. He cannot do it unless he is going. If he finds he is falling, say on the right hand, he steers *to the right*—his inertia carries him forward on his first course, *across* that into which the bicycle has been directed, and this movement restores him to a position above the line of the wheel base. If he was going fast and made a short turn, he may overbalance on the other side, and will be obliged to turn his wheel to the left. The action and the response are quite sensitive, and with very little experience the rider falls into the practice almost unconsciously.

2. *The alteration of motion is ever proportional to the motive force impressed; and is made in the direction of the right line in which that force is impressed.*

If a body is changed in its motion, we may be sure it is because a force has been brought to bear upon it, and by the "alteration of motion" we are to understand the rate at which the entire *quantity of motion* in the body is altered. That term "quantity of motion" is no longer employed, but Newton stated that he used it to express the product of the amount of matter in the body by the velocity with which it was moving; the mass by the velocity—a quantity for which we now use the term *momentum*. If we call the mass of a body m, and its velocity v, its momentum is mv; and if we represent the time during which the momentum is being changed, or the force

is acting, by t, then the rate of change in momentum is mv/t. Now this is precisely the same as the product of the mass m by the rate of change in v, or the acceleration v/t, so the rate of change in momentum is precisely the same as the mass multiplied by the acceleration.

Just what are we to understand by the expression "one quantity is proportional to another"? It means this: That the two things are so related to each other that one is always a definite, constant number of times as great as the other. If the second changes by any amount, the first will change so much as to make it again the same number of times as great as the second that it was before. If A is proportional to B, A is some number of times (always the same number) once, or twice, or half, as great as B.

We have from experiment that the force F that changes the motion of (accelerates) a body is proportional to the mass m, and to the acceleration a, and is therefore equal to some number k times their product, or $F=kma$.

How much the number k is depends upon the units by which F, m and a are to be measured. Usually these are so related to one another that $k=1$, and the equation as commonly used is $F=ma$.

In the above equation, where $F=kma$, we already have the pound fixed for measuring m, and we also have the foot and the second as units for measuring distance and time, and from these, the unit for a; and F is the only thing for which we have no unit. But if we wanted to measure forces by using a unit force such as would give to a pound mass an acceleration of a foot per second in a second, then, since F would be 1 when m and a were each 1, k in the above equation would be 1, and $F=ma$. Such a force for a

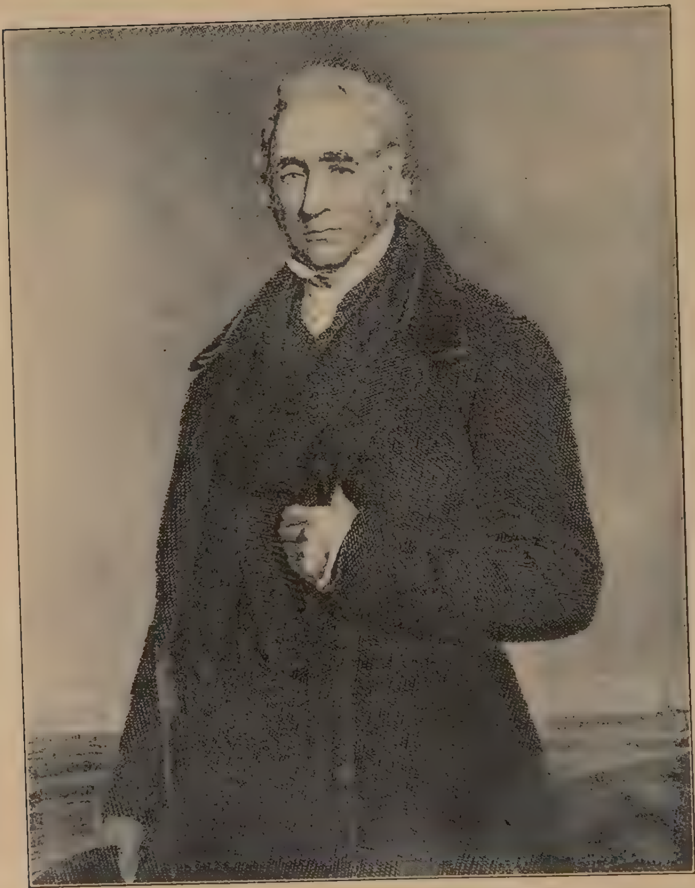
unit, however, would not be the weight of a pound, for a force of one pound applied to a mass of one pound will give it an acceleration not of one foot per second per second, but 32.2 times as much. *We do not know why it should, but it does.* If we adhere to the pound for the unit of mass, the foot for the unit of distance, and the second for the unit of time, then one foot per second is necessarily the unit of velocity, and the legitimate unit of force is only about 1/32 as great as the weight of the pound. That small absolute unit of force which gives to a pound mass an acceleration of one foot per second per second is called a *poundal.*

ABSOLUTE UNITS AND GRAVITATION UNITS

Any system of measurements that is based upon the fundamental units of length, mass, and time, is called an "absolute system," while one in which force is determined by weight is called a "gravitation system." In pure science it is much more satisfactory to use the absolute system, but in everyday practice, and often in engineering, the gravitation units are used. We can reckon the force F in pounds and still have it numerically equal to the mass m, multiplied by the acceleration, if we use a larger unit for the mass, namely 32.2 times the pound, for that is the mass to which a force of one pound would give a velocity of one foot per second if it acts for a second. Then the mass of a body would be only 1/32.2 part as many units as the number of pounds in it.

We can always say "force equals mass times acceleration," but we cannot have force and mass both in pounds at the same time, for they do not go together. If the mass is pounds, the force is poundals, and it takes 32.2 *poundals to equal the weight or a*

ROBERT FULTON



GEORGE STEPHENSON

force of one pound; if we want to figure upon pounds for FORCE, *we must consider the mass* M *to be the number of pounds in the body divided by* 32.2.

ACCELERATION OF GRAVITY; VELOCITY ACQUIRED AND DISTANCE TRAVERSED BY A FALLING BODY

The fall of a body to the earth is said to be due to the force of gravity. Without knowing just what gravity may be or how it acts, we may think of it as a force pulling the body downward, just as the force in the spring balance shown was pulling the body horizontally. By experiment it is found that if the fall is not impeded in any way, then in the first second the body falls sixteen feet and acquires a velocity of thirty-two feet per second; at the end of the next second it has a velocity of sixty-four feet per second; at the end of the third, ninety-six feet per second, and so on, adding a velocity of thirty-two feet per second in each successive second of time, and this increase is called the acceleration due to gravity, or, briefly, the acceleration of gravity. It is more exactly 32.17 feet at sea level in Lat. 45 degrees, for which 32.2 is a close approximation, and for not very accurate work 32 will answer. In metric units it is 980.6 cms., and in any system is represented usually by the letter g.

The velocity acquired by a falling body at the end of any number of seconds equals gt., "t" being the time in seconds. The total distance fallen equals $\frac{1}{2}gt^2$.

ILLUSTRATIONS OF THE SECOND LAW OF MOTION

The second law is very comprehensive, as it gives us to understand that a body under the action of several forces will obey each and every one of those

forces, and that the effect of a force is not influenced by the condition of the body, such as its being already in motion, when the force is applied, or by any other quality that it may have, such as temperature, color, wetness or dryness, etc. Since force equals momentum divided by time, force multiplied by time equals momentum, which may be written $Ft = mv$. Here Ft represents the *action of the force* for a definite time, and mv is the *effect produced on the body* in the way of motion; the former is called the impulse applied, the latter the momentum that is acquired; and always the impulse equals the momentum.

The equation is beautifully illustrated, in connection with inertia, by attempting to put a body into motion suddenly. Attach a string to a heavy object, and jerk violently upward. To follow the pull of the string the body would have to move rapidly in a very short time; that means a rapid acquisition of momentum, and that, in turn, means a large force—large enough to break a string, which would be quite strong enough to lift the body slowly, i. e., to communicate a moderate momentum within a brief time. It is the string instead of the body that actually does the yielding by stretching to its breaking point before the body is raised.

CONJUNCTION OF FORCE AND TIME IN RELATION TO MOMENTUM

Just as force in a conjunction with time is required to increase the momentum of a body, so it is requisite to diminish it or to bring the body to rest. If there is large momentum (and that might be the case either with a large mass and no great velocity, or with small mass moving with great velocity) we

can see at once what force would be required to stop a moving mass in a given time, for $Ft = mv$, and when a body has a known momentum, mv, if a *small* force is to change the momentum from something to nothing, i. e., bring the body to rest, it is plain that the time t must be large: or if the time t to bring it to rest is small, evidently F will be large. It is in this wise that a mathematical formula expresses real facts of physics.

It is not uncommon to hear a question like this: "If a stone is struck by a hammer weighing 20 pounds, with a velocity of 30 feet per second, what is the force of the blow?" Keeping in mind that if we want to express the force in pounds, mass m is pounds weight divided by 32, then momentum would be $\frac{20}{32} \times 30$, or $18\frac{3}{4}$ units, and if this is to be destroyed (the hammer to be stopped) in 1/100 of a second, the average force against the stone would be $18\frac{3}{4}$ divided by 1/100, or 1,875 pounds. But if the hammer had struck a bag of sand and was stopped in 1/5 sec. since the force was in effect twenty times as long, it was only one-twentieth as great, or less than a hundred pounds. So long as time is not stated, or, as we shall see later, the distance passed over, the answer to the question is wholly indefinite.

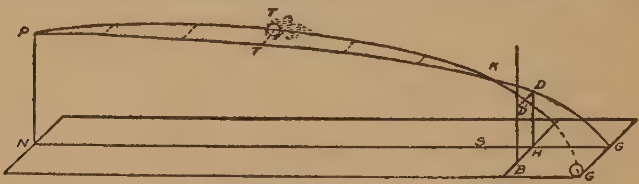
HOW A PITCHED BASEBALL IS "CURVED," AND A TENNIS BALL "CUT"

The second law in connection with inertia also accounts for the "curve" which a pitcher gives to a baseball, or for the "cut" of a tennis ball.

In the figure, suppose the pitcher to be at N, the line from him to the batter at B being from north to south. A straight delivery from P has the

trajectory PTDG, passing over the home plate H at D, and if not caught, reaching the ground at G. If the ball had been projected from P slightly eastward of the line NS, but with a right-hand spinning movement, it would have been deflected to the right as it advanced, have crossed the other path, say at K, have crossed the line BH at D′ with an "in-shoot," and, if not caught, would have struck the ground at G′.

A ball moving forward without rotating is equally pressed by the air on both sides and therefore is not deflected laterally. If, however, it is rotating clockwise, the left side moves forward and the right side



PATH OF A BASEBALL WITH AN INCURVE

backward, in addition to the forward movement of the ball as a whole. The air is compressed upon the left side and rarefied on the right by the rotation, increasing the side pressure of the air on the left and decreasing that on the right, and the ball is deflected to the right. The diagram illustrates this distribution of pressure against the ball. If it were rotating vertically, its path would curve up or down according to the direction of rotation; it is always deflected to that side toward which the front is turning. With this same velocity of projection and rotation, the deviation is more rapid the lighter the ball; this is strikingly shown in the much greater curvature given by the "cut" of a tennis ball. A

rough cover on the ball also helps to increase the pressure effect on each side, and so to increase the curve. Probably the effectiveness of the so-called "spitball" may be due somewhat to this, and to the better grip it affords the pitcher, enabling him to spin the ball faster.

Newton's third law of motion is:

3. *To every action there is always opposed an equal reaction; or the mutual actions of two bodies upon each other are always equal, and directed to contrary parts.*

To this law we have already given some attention.

The preceding consideration of the laws of motion makes it possible for us now to present the following scheme of mechanical units in both the British foot-pound-second (or f. p. s.) system, and the metric centimeter-gram-second (or c. g. s.) system.

British = f. p. s.

1 foot = 1/3 of the length of the metal bar authorized by Congress as the standard yard.

1 pound mass = the amount of matter in the piece of platinum authorized by Congress as a standard pound. It is the absolute unit of mass in the f. p. s. system.

1 poundal = the force which will change the velocity of a pound mass by 1 foot per second, in a second of time. It is the absolute unit of force in the f. p. s. system.

1 pound force = the force which will change the ve-

Metric = c. g. s.

1 centimeter = 1/100 of the length of the metal bar authorized by the French Government as the standard meter. It is the absolute unit of length in the c. g. s. system.

1 gram mass = 1/1000 of the matter in the piece of platinum authorized by the French Government as the standard kilogram. It is the absolute unit of mass in the c. g. s. system.

1 dyne = the force which will change the velocity of a gram mass by one centimeter per second in a second of time. It is the ab-

British = *f. p. s.*	*Metric* = *c. g. s.*
locity of 1 pound mass by 32.2 feet per second or that of 32.2 pounds mass by 1 foot per second in a second of time. It is the gravitation unit of force in the f. p. s. system.	solute unit of force in the c. g. s. system. 1 gram force = the force which will change the velocity of one gram mass by 980 centimeters per second or that of 980 grams mass by one centimeter per second in a second of time. It is the gravitation unit of force in the c. g. s. system.

One second = $\frac{1}{86400}$ of the duration of a mean solar day. It is the absolute unit of time in both the f. p. s. and the c. g. s. system. Also:

1 yard = 0.914 meter.	1 meter = 1.0936 yards, or 39.37 inches.
1 inch = 2.54 centimeters.	1 centimeter = 0.3937 inch.
1 pound mass = 453.59 grams.	1 gram mass = 0.002205 pound.
1 pound force or 32.2 poundals = 453.59 grams.	1 gram force or 980 dynes = 0.002205 pound force.
1 poundal = 13,800 dynes.	1 dyne = 0.000072 poundal.

CHAPTER X

CENTRIFUGAL FORCE

WHEN a wheel or a grindstone is turned rapidly, particles at the rim fly off, or the wheel may actually fly to pieces if the speed is very great. No driver of a vehicle, or traveler in it, but is annoyed by the mud or water that flies off the rim of the wheels. An inspection of the way the flying bits move shows that they do not go out in straight lines from the center, but simply go forward in continuance of the direction they had when they became detached; i.e., they move in a tangential direction.

It is always impressive as well as pleasing to a boy when he discovers that he can whirl a pail of water in a vertical circle without spilling any, even when it is inverted above him. That there is any resemblance between this performance and the revolution of the planets around the sun is not in his thought, and is perhaps beyond his comprehension, yet we can, with little difficulty, not only trace out such an analogy, but see that the movements of the heavenly bodies are, in fact, the whirling of the pail multiplied and extended to the scheme of the universe.

We have seen that the effect of a continued application of a force to a body that is free to obey it is to change its velocity steadily, which change is

called acceleration, and the measure of the force is the mass multiplied by the acceleration. Furthermore, a body will not be so changed in velocity unless a force is applied to it; not even its direction of motion will be altered unless a force is exerted to deflect it.

If the body is moving in a curved path, its direction of motion at any point in the path is that of a tangent to the curve at that point, and if the body does not go straight on along that tangent we may be certain that some force is acting upon it at right angles to the tangent. If the body is moving in a circle, that deflecting force is then directed toward the center. The body may be compelled to follow the circular path by a string that holds it, or by a circular rim outside the body. There will then be a pull upon the string or a pressure upon the encircling rim. The departure of the body from its straightforward path constitutes *a change in velocity,* though only as to direction. Mathematical demonstration and experiment both show that the rate per second at which this change is effected is the square of the velocity of the body divided by the radius of the circle it is describing. This is acceleration, and, as we have already learned, the force necessary to bring about that rate of change is the acceleration multiplied by the mass of the body, or $\frac{mv}{r}$.

This is the force which must be applied to the body to push or pull it *toward the center,* and the reaction of the body against such an applied force is called "centrifugal force."

So far as the string is concerned, it is pulled as hard outward as inward, and it would not know whether it was sustaining a centripetal or a centrif-

ugal force. In fact these are simply two aspects of the stress in the string. There is, however, at no time any tendency of the body to fly out directly from the center; the tendency is to move on tangentially, and the centripetal force is just that which is required to deflect it from the tangent into the given circular path. When, therefore, that force ceases to act, there is no reason to expect that the body would go in any direction except *straight on*—as in fact it does.

EXAMPLES OF CENTRIFUGAL FORCE

Like all natural agencies, centrifugal force may bring about disaster if not controlled, or it may be of great utility. If a train of cars strikes a curve at a high speed, it will be hurled from the track unless the outer rail is so elevated as to give the car a lean inward that counteracts the outward tendency.

In large laundries, centrifugal action has long been employed for drying clothes. Now, by the help of an electric motor to produce a high speed of rotation, the same means has been brought within the reach of the single household, and laundry machines of a small size are in use in which the power wringer is replaced by a centrifugal drier. Its operation is interesting, and its actual effect easily calculated. A cylinder with perforated sides contains the clothes just washed and ready for wringing or drying. The cylinder is set rotating rapidly by an electric motor, and the pressure of the clothes against the cylinder surface forces out the water effectually.

A vessel containing water may be whirled around vertically without spilling any of its contents if it

has sufficient speed. In such case the centrifugal force must be at least equal to the weight of the material rotating, and this depends upon the length of the radius and the speed with which the body is moving in its circular path. In the "centrifugal railroad," on which passengers are carried round a vertical circle in a "loop the loop" car, the same principle is applied to calculate the velocity required for safety in such cases. Take the equation for centrifugal force, $F = \frac{mv^2}{r}$, and transform it by substituting for m its equivalent w/g, for we have before seen that when pounds are considered as force, mass (m) becomes weight (w) divided by the acceleration of gravity (g). Also for F substitute w, since in this case the weight of the whirling body measures the force, then the equation becomes $w = \frac{wv^2}{gr}$, and, by transposition, $v^2 = \frac{wgr}{w} = gr$. Now, if the vertical circle is 50 feet in diameter, its radius (r) is 25 feet. But g equals 32, so that gr is 800. Therefore v, the velocity which the car must have at its highest point, is the square root of 800, or about 28¼ feet per second. The same formula applies in the case of the pail of water whirled over the head, and in all similar cases.

Whatever may be the nature of gravitation, it presses a body to the earth with a force which we recognize as the weight of the body when we attempt to lift it or separate it from the earth. As the earth and the bodies upon it are rotating about an axis at the rate of one revolution in twenty-four hours, the bodies all have a centrifugal tendency, and their pressure upon the earth—that is, their weight—is less than it would be if the earth were not rotating, by just as much as the force required to hold them to their circular paths.

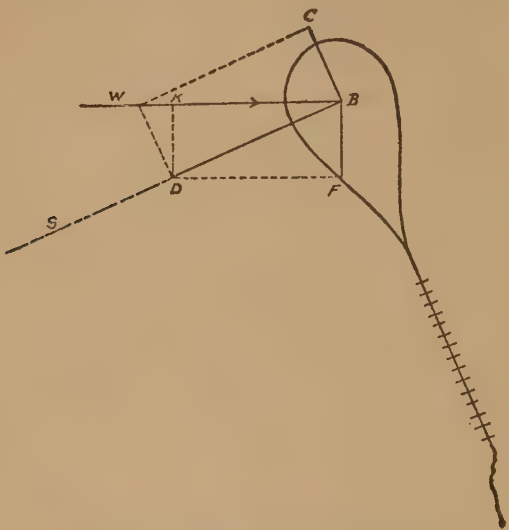
This diminution in weight is easily calculated, for we know the radius of the earth and the speed with which the body describes its revolution around the axis, and from these data we can compute the centrifugal force. At the equator it is equal to $\frac{1}{289}$ of the weight of the body.

The force is proportional to the square of the velocity; 289 is the square of seventeen; so, if the earth turned seventeen times as fast, the centrifugal force would be 289 times as great, or, at the equator, just equal to the weight of the body. That is to say, bodies on the equator would have no weight. If a shot were projected in the direction of the rotation, at that velocity, amounting to about 4.9 miles per second, and not checked by the air or other obstacle, it would steadily pursue an orbit around the earth like a little satellite, neither falling to the earth nor departing from it.

COMPOSITION AND RESOLUTION OF FORCES

If a force were applied to a body to lift it, the force would be most effective in a vertical direction, for then no part of the effort would be expended to move the body except in opposition to its weight, which acts vertically. If the force were applied horizontally, there would be no effect toward lifting the body; all the effort would be to move it without raising it. If the force were applied in any intermediate direction, there would be some tendency to lift the body and some to move it horizontally. The applied force would represent the combined action of two forces, one horizontal and the other vertical, each less than the original which might be replaced by them. Those two would produce a combined effect just equal to that of the one. When any force is

thus replaced by two or more others which together are equivalent to it in effect, it is said to be resolved into those several "components," and when two or more forces are replaced by a single one equivalent



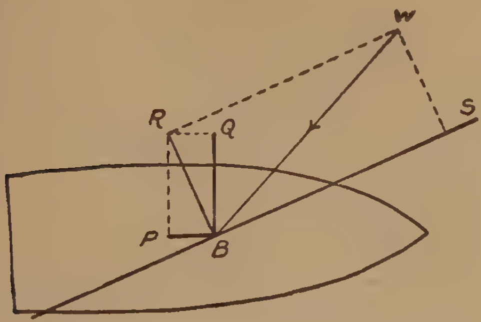
ACTION OF THE WIND AGAINST THE SURFACE OF A KITE

WB represents the force of the wind blowing horizontally against the kite, the force being, we may say, concentrated along *WB* and applied at *B*. Its effect upon the kite would be that of a force *DB* perpendicular to the surface, and *CB* along the surface. Only the former has any pushing action, and the string takes the direction *BD*. This push may be regarded as the resultant of two forces; *KB* acting horizontally, and *FB* vertically upward. This last represents the lifting effort of the wind upon the kite.

to them in effect, they are said to be combined into a "resultant."

The entire subject of composition and resolution of forces belongs to a detailed study of mechanics, the simplest case being that of two forces and their resultant applied at a point, the forces being at

right angles to each other. The forces then may be represented by the two sides of a rectangle, and the resultant by the diagonal. If a force, such as that of wind, for example, is directed against a surface



ACTION OF FORCES IN SAILING A BOAT AGAINST THE WIND

S represents the sail, *WB* the wind, which we may suppose concentrated at *B*. It may be regarded as consisting of a force *SB* along the sail surface and therefore not effective, and another, *RB*, perpendicular to the sail. This, in turn, is equivalent in effect to a component *QB* driving the boat transversely and *PB*, pushing the boat forward. The rudder has to counteract the forces driving the boat to leeward.

obliquely (like the surface of a kite or a sail), it may be regarded as made up of a component acting perpendicularly to push against the surface, and another component parallel to the surface and having no effect in moving it.

CHAPTER XI

WORK AND ENERGY

ON preceding pages we have expressed the result of experiments with various forces in moving bodies. In these experiments we treated the force in conjunction with the time during which it was applied to the body, and the effect in terms of the mass of the body and the velocity conferred by the force.

Whether by calculation or by direct experiment, only noting distances and velocities, we should find that the force multiplied by the distance equals half the mass multiplied by the square of the velocity, or Fs (s standing for distance) $= \frac{1}{2} mv^2$.

When a force is applied in moving anything it is said to do work, and the measure of the work is the product of the force by the distance through which it moves the body or overcomes the resistance; i.e., Fs.

Now observe the effect on the body. If the latter is perfectly free, and starts from rest, it acquires a velocity v. When moving with this velocity it has the capability, on its part, of overcoming, or changing, other bodies which it had not before the work was done upon it. It has acquired energy represented by the $\frac{1}{2} mv^2$.

This is the equation of energy, and is highly important in physics, the first member, the work, signifying the action of the force, and the second, the effect on the body; and the work done equals the energy acquired. The force is here the change of

energy divided by the distance. But while the work is done by the force moving through a distance s, the result may leave the body not in motion, but in a state or a position in virtue of which it has the ability to do work, or to effect a change in bodies. If a weight of one pound is raised from the floor and placed upon a table at the height of one foot, a force of one pound has moved the object one foot in the direction in which the force was exerted, and the work thus done is called a "foot-pound." This is taken as a unit, in common practice, for measuring work. If the body had required a force of five pounds to lift it and it had been raised ten feet, the work would be fifty foot-pounds. The body lying on the table is at rest, but ready to return to the floor if allowed to do so by the removal of its support.

When a bow is held by a taut string, and the arrow, pressed against the string, is drawn back, force is applied to bend the bow, and when it is held in that bent position, work has been done upon the bow, and the latter, though not in motion, has the capability of doing work on its own account: it possesses energy, although not in motion. It is in a state of strain. Its energy, like that of the weights on the table, is static, while that due to the motion of a body is kinetic, but because of the potency of the body even when quiet, its capability has been termed "potential energy."

Both work and energy are expressed in the same terms; in the f. p. s. system of units the absolute unit of force, a poundal, moving a body a foot does a foot-poundal of work; a force of a pound, moving or lifting a body one foot does a foot-pound of work. In the c. g. s. system the absolute unit of force is a dyne, and the work of one dyne through one centi-

meter is an "erg." This is an exceedingly small unit, and is usually replaced by one ten million (10^7) times as great, or 10^7 ergs, which is called a "joule."

WORK SHOULD NOT BE CONFOUNDED WITH POWER

Work or energy is a distinct quantity, measured in its own appropriate units. When 100 foot-pounds of work is done or energy expended, it has its definite value, whether it was done in an hour or in a minute. But the rate of doing it would be very different in these two cases, and the word to designate the rate of doing work is "Power." It is measured, not by the total amount of work, but by the amount per unit of time: foot-pounds per minute, or ergs per second.

A common unit of power in engineering practice is the "horsepower" (H. P.), which is 33,000 foot-pounds per minute, or 550 foot-pounds per second, these being the same rate. To work at one horsepower it is not necessary to do 33,000 foot-pounds of work, or to keep working for a minute—one-tenth of a foot-pound done in $\frac{1}{5500}$ of a second would be one horsepower, and a million foot-pounds would be done by one horsepower if 30.3 minutes were occupied in doing it. The term "horsepower-hours" is sometimes used to express the result of working at the rate of so many H.P. so many hours. It becomes, of course, simply work, or foot-pounds.

In metric units the rate of working is more commonly called "activity" instead of power, and an activity of one joule per second is a "watt," 746 watts being the same rate of working as one horsepower. A unit of one thousand watts is more common in measuring power on a large scale. It is called a "kilowatt," and equals 1.34 H.P. The term

kilowatt-hour corresponds in sense (not in amount) to horsepower-hour in the British system of units.

ENERGY PRIMARILY POTENTIAL OR KINETIC

The energy of a body, or system of bodies, is necessarily either potential or kinetic, or is shared between the two. These are the main heads under which the forms of energy are classified, and the energy of a body may change from potential to kinetic or the reverse.

If a body is supported at an elevation, it has potential energy with reference to the earth, for work had to be done to take it from the earth to its higher position, and if its support is removed, it will fall to the earth, acquiring kinetic energy as its potential energy decreases, until, when it reaches the earth again, the energy has completely lost its potential character and has become entirely kinetic. The body can now do work in consequence of its motion, and in being brought to rest will do an amount of work equal to its energy. If the body, on its way down, had worked a machine, and reached the earth at a standstill, it would have given up energy exactly equal to the work of raising it from the ground in the first instance; that is the way the energy of a waterfall is used. Evidently, while *en route* from its elevated position to the earth, at every stage of its progress it possessed some energy both potential and kinetic; and if not expended in overcoming some resistance, what it lost of the former was exactly made up by its gain of the latter.

VARIOUS FORMS OF ENERGY; WHAT THEY INDICATE

Under these two general heads, what are the various forms in which energy—this elusive yet ever-

present something—manifests itself? We can identify a number of forms under each head, which we may consider briefly here, and develop more fully in their respective places in physics.

The first of these under potential (strain) is seen when an elastic body is twisted or bent, as in a spring. The second is seen in a body separated from the earth; it is at a higher level, where it can only have been put by work or energy expended upon it, and then, though quiet, it has potential energy by virtue of its separation, which energy is transformed into kinetic, or into work, as the body returns to the earth and the separation no longer exists.

In like manner, if bodies are impelled to join one another by any action between them other than that of gravity, as, for example, by electrical or magnetic attraction, while they are separate they are under constraint, and can do work in reuniting, so they have energy of separation.

When carbon and oxygen are separate, neither evinces any special capability by reason of being what it is, but upon their union, in the process of combination, heat is liberated, which is energy pure and simple. While separate, they had the potentiality of the heat liberated later in their combination. In the high-explosive shell, the charge may be, say, tri-nitro-toluol (TNT); this substance is an unstable compound. In the shell, a detonation causes a readjustment of the constituents of TNT, with a recombination that evolves enormous quantities of gas, with intense heat, and the potential energy of chemical separation becomes evident with this recombining.

Of the forms grouped under "Kinetic," the energy is all evidenced in the work or physical change they

are able to effect. 1, in the work required to deprive a body of its motion, or the resistance the body can overcome in moving through a distance. 2, the internal or molecular work by which vibrations are steadily diminished—or the production of sound. 3, heat produced by the interception of radiation, as when a body warms in the sunshine. 4, mechanical work accomplished by heating a gas. 5, magnetic and heating effects of a current.

ENERGY OF TRANSLATION CONVERTED INTO ENERGY OF ROTATION, AND CONVERSELY

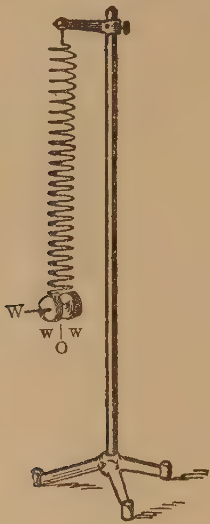
Instances are abundant showing the capability due to kinetic energy, in every state in which matter exists; whether as a solid, it be the ponderous blow of the massive battering ram, or the destructive rush of the irresistible avalanche; as a liquid, the gigantic power of the flowing river in beneficent use as at Niagara, or the destructive action of floods; as a gas, the wind in its useful service of turning the sails of mills or propelling ships, or in the devastation of the tornado.

But not only in the rush of matter that is traveling onward is kinetic energy recognized and utilized. To set a body rotating, or, if it is already in rotation, to speed it up or to check or stop it requires work to be done, and the energy of rotation is a potent factor in the action of machines. The details of such applications and their mathematical development are better left to special works on mechanics, but a striking example of the change from energy of translation into that of rotation and the reverse is afforded by the "Wilberforce Spring."

In this a weight, W, consisting of a crossbar with two small weights, is suspended from a spiral

spring. When W is drawn down and released it oscillates up and down *in a definite period of time,* with energy of translation that becomes static at the highest and lowest position, where the body is momentarily motionless.

Instead of setting W oscillating vertically, by turning it some distance around the vertical axis of the



THE WILBERFORCE SPRING

This shows exchange of energy of translation with energy of rotation.

coil and releasing it, it will vibrate around and back horizontally *in a definite period of time,* with energy of rotation that is wholly kinetic at its mid stage, and static at its extremes, where it is momentarily motionless. By moving the small weights outward from the center O, the period of oscillation may be lengthened or by moving them inward toward O the period will be abbreviated, and in this manner

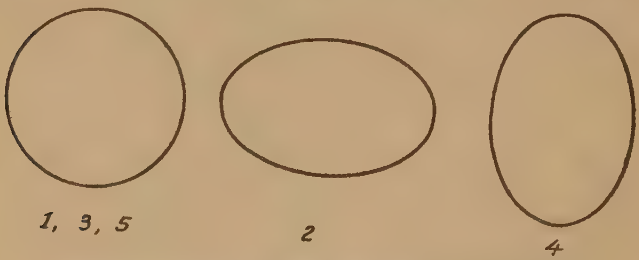
W may be adjusted until the period of horizontal oscillation is the same as that for the vertical. When this is the case a remarkable transformation of energy may be observed. Twisting ww around horizontally tends to wind up or unwind the spring and introduces a vertical force in it. As W rotates, the spring draws it up or lets it down slightly, each horizontal swing adding somewhat to this vertical action. The horizontal action decreases and the vertical grows until the rotation ceases entirely, and W will be found to be oscillating only up and down. Energy of rotation has been changed completely into energy of translation. But every elongation of the spring introduces in it a twisting or turning effort, and now, with every rise or fall of W a force is produced in the spring to turn the weight slightly to the right or left. This steadily increases while the vertical movement decreases, and presently the motion is again wholly one of rotation about the axis of suspension; energy of translation has been changed completely into energy of rotation, and the reciprocal exchange is kept up until the movement is stopped altogether by the resistance of the air and molecular action in the wire.

VARIOUS MODES OF MOTION

When a body is in motion, all its parts may be advancing at the same rate, all moving ahead in equal parallel paths; or some point or line in the body may be fixed and the body may swing around the point or line as an axis. The former is called a motion of translation, the latter, rotation. A rotating body may also move onward at the same time, its axis also going along, and the body then has both kinds of motion. All movements of a body are

comprised in these two forms and one other. In this other, the body, or any part of it, goes through a series of movements, and then returns through the same movements in opposite direction and reverse order. This, which may occur in numerous ways, is termed, broadly, vibration, and will be considered separately.

Newton's laws are considered to apply directly to the first class of motions—translation. That is sufficient for the others also, when we consider that a particle, the very small part of a body that is practically at a point, even if swinging around an axis,



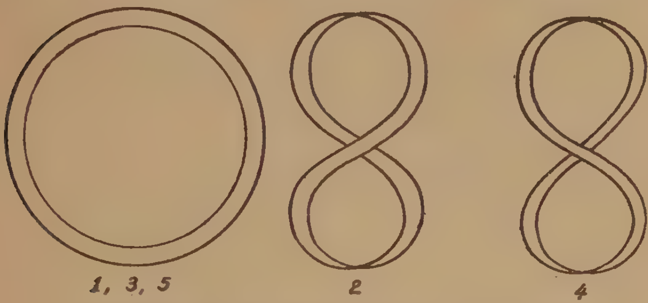
VIBRATING BODIES—FORMS ASSUMED BY A SPHERE

If a sphere of india rubber be propelled against a hard floor, it may change its form, as, from 1 to 2, to 3, to 4, to 5, and so on. A ring may assume similar forms in vibrating, or it may change as in the next illustration.

is at any instant moving in the definite straight-line direction of the tangent to its curved path, and if it is oscillating to and fro, any change of motion has, for the moment, a definite linear direction.

Vibration is usually understood as a simple motion to and fro, rapid enough sometimes to be a tremor, but in physics, as a science of occurrences in nature, its meaning is much more extended. There are any number of ways in which a body may vibrate—so many and so varied, indeed, that the term is now

applied to any periodic movement, and by that is meant the passage of a body through a series of shapes or positions regularly, the body returning to its initial position in equal periods of time, to repeat its cycle of changes in the same order as before. Applied to an elastic body, as a ball or a ring, it may dart back and forth, or revolve around a center, or



VIBRATING BODIES—FORMS ASSUMED BY A RING

A ring may pass through changes resembling those illustrated by the sphere diagram, or it may pass through the set shown herewith—from 1 to 2, to 3, to 4, to 5.

change its form, and do these things separately or partake of them all in one period. This would be vibratory motion. In its simpler forms, however, it is simply a swinging through a neutral or mid position to an extreme, from which it returns through its mid position and on to a corresponding extreme on the other side, and again to its initial position; like the swing of a pendulum or the vibrations of an elastic bar clamped at one end, pulled aside, and then let go.

In all cases the vibrating body has energy. If it is a spring with one end clamped and the other end drawn to one side, it then has potential energy

equal to the work of bending it; when released it returns to its initial position with no strain there, but a rapid motion, such that kinetic energy has taken the place of its potential energy, and, in consequence, it goes on to the opposite position, at which all the energy has again been expended in bending the spring, and the process is repeated in reverse order.

CHAPTER XII

ELEMENTARY MACHINES

IN the early days of science, when an investigator solved, or thought he had solved, some perplexing question, it was common to issue a challenge or offer a prize for other solutions. This was notably the case in mathematics, and mathematicians spent much ingenuity in finding as many different ways as possible of proving the same thing! Hence the numerous demonstrations of famous geometrical theorems. It became quite a game, and was kept up well into the eighteenth century, and early cropped out in connection with knotty problems in physics where it took on a slightly different form.

A so-called "mechanical advantage" is obtained by any machine in which a small force overcomes a large resistance, but we shall see that even in these there is always loss in some form that exactly counterbalances the gain. It has been usual to present the elementary forms of machines for mechanical advantage, as the six "simple mechanical powers" and to treat each as a separate case. They are the lever, the pulley, the wheel and axle, the inclined plane, the screw, and the wedge. The first three of these can be shown to be fundamentally alike in their action, and the use of the lever is too familiar to need describing; but there is no necessity whatever to separate levers into three classes, as is sometimes done.

Very crude experiences soon taught man that while such a force as he could exert might not suffice to raise a weight vertically, the same force would take even a greater load up an incline, and the less steep the inclination the greater weight he could raise. A device constructed to be used in this way is called an "inclined plane," and the screw and the wedge are modified forms of this.

It is possible to deal with all the six "powers" in one definite way. Here is where the tendency to seek various solutions was followed by different physicists. Several such general modes of treatment have been developed, but one is sufficient here. This is the relation that holds in any machine, between the force that is applied and the resistance that is overcome.

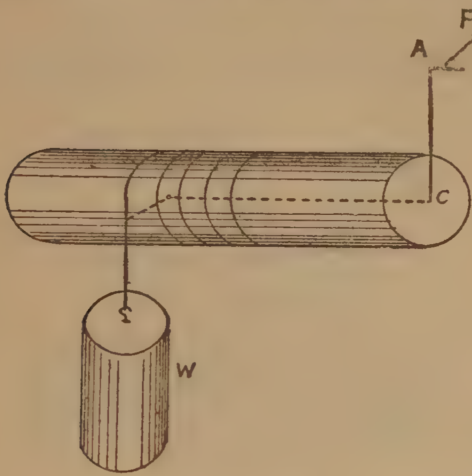
The force multiplied by the distance it moves (in the direction of its action), equals the resistance multiplied by the distance through which it is moved (in the direction of its action). If the force is applied at the end of a crank it ought to be directed at right angles to the crank arm, i.e., the radius of the circle described, and if the resistance is a weight raised, its distance should be measured vertically.

Generally, by merely inspecting the form of the mechanism, it is possible to determine how far the resistance will be moved with a given distance of moving the force, and then their relation is easily calculated. In some instances other means are easier to apply.

Suppose the crank arm of the winch to be one foot, and the radius of the axle on which the cord is wound to be four inches, or 1/3 foot. In one complete turn of the crank the force P will describe a distance equal to the circumference of a circle of

one foot radius, or 6.28 feet, and the weight W will be raised a distance equal to the circumference of the shaft, or only one-third as far as P moves; therefore the above principle shows that W = 3P, or one pound force will raise three pounds of weight.

In the screw, one turn of the screw advances it in the direction of the axis the distance from one

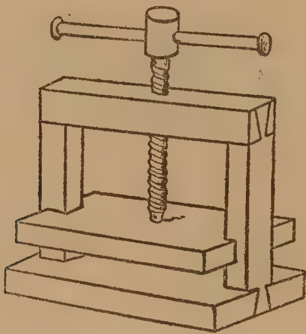


THE WINCH

One of the common forms of simple mechanical powers.

thread to the next. Suppose the distance from the axis to the end of the handle through the head of the screw to be one foot, and the distance from one thread to the next to be one-half of an inch. Then, in one turn of the screw by a force R applied at the end of the lever, P moves 6.28 feet, and the resistance is pushed along 1/24 of a foot; and P x 6.28=W x 1/24 or W is 150.72 times as great as P.

With the screw and cogged wheel, one turn of the screw moves the wheel from one tooth to the next. As there are seventy-two teeth in the wheel, the screw must revolve seventy-two times to turn the wheel once. If the crank arm is say, one foot, and the radius of the shaft of the wheel is one-sixth of a foot, and the latter pulls a weight by a cord wound around it as in the case of the winch, then the force P would have to make seventy-two turns, or traverse a distance of seventy-two times 6.28 feet, to pull the resistance a distance equal to the circumference of



THE SCREW

Another of the common forms of simple mechanical powers.

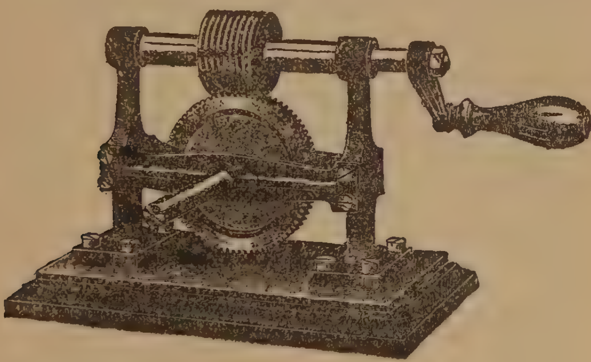
the shaft, or 1.04 feet; or the force could overcome a resistance 432 times as great as itself.

It is plain that whenever a small force overcomes a large resistance it traverses a large distance to move the resistance a small distance, so that *whatever is gained in power is lost in velocity or distance.*

FRICTION; ITS EFFECT NOT ALWAYS A DISADVANTAGE

It must, of course, be kept in mind that in all these theoretical considerations of machines the results

are correct only when no other agencies are acting than those considered. Friction is always present in some measure, and always requires some force to overcome it, so that the mechanical advantage is less in fact than in theory. In the pulley and the lever the resistance of friction is usually not serious; in the screw and the wedge it is very great. To some extent frictional resistance under different degrees of lubrication have been determined experimentally,



SCREW AND COGGED WHEEL

Combining two simple forms of mechanical power.

but any reliable application of those results is a matter for advanced mechanical engineering.

In many modern machines, the work of friction is greatly reduced by "ball bearings." These are hard steel cylinders or balls, on which the revolving shaft or plate rides instead of rubbing upon its bearing, and which turn under the shaft as it moves.

But friction is not to be regarded as always objectionable. Its advantages are inestimable: it is the most common means of applying a brake, and

in that way it is often of great use in preventing a machine from running away.

From a boat pulling alongside of a pier, a hawser is tossed to a laborer who gives it a turn or two about a snubbing post, and holds back as the pull of the boat tightens the rope. If the rope has made two turns around the post without any overlapping upon itself, the frictional resistance of the rope coiled upon the post is so great that a pull of one pound upon the free end of the rope will withstand a draw of nearly one hundred and fifty pounds, or a pull of five tons by the boat will be withstood by one of less than seventy pounds by the man on the pier.

The danger and difficulty of walking on ice or any slippery surface is well known; without friction on the ground neither man nor beast, ordinary carriages nor locomotives, could move on. We could hold nothing in the hand unless the hand were directly under the object. Without friction buildings could not be erected, nails and screws would not hold, even hills and mountains would gradually disappear, and dry land would finally sink beneath the sea.

CHAPTER XIII

GRAVITATION

BEFORE the adoption of the Copernican system of astronomy, the belief was current that the earth was fixed in position and that bodies all tended toward it. When the new theory was propounded, declaring that the earth not only rotated upon its axis but also, with the other planets, revolved around the sun, its discussion violently disturbed the earlier placid notions of terrestrial stability. The observations of Tycho Brahé, and more especially of Johann Kepler, gave a basis for expressing the movements of the heavenly bodies in a well-defined method, which was perceived and demonstrated by Sir Isaac Newton. His problem was to determine what principle of action, or what forces, would account for the motion of the heavenly bodies so as to conform to the Copernican idea of the solar system.

Out of his cogitations upon this question grew the wonderful idea of universal gravitation; not only a tendency of bodies to fall to the earth, but a tendency of all bodies toward one another, and with a clearly defined measure of the force so impelling them.

The idea is said to have come to the great philosopher as he was seated in his garden at Woolsthorpe, England, when his attention was caught by the fall of an apple to the ground from a neighboring tree. If the apple, on being detached from its stem, had

risen instead of falling, and had gone sailing aloft into the empyrean, its performance would have been astonishing, but really no more mysterious than when it fell downward; and that is what set Newton thinking. Any influence by which bodies tend to come together of themselves, requiring a force to prevent them from so doing, is termed in general, "attraction"; and in the case of mutual action among material bodies which is dependent on the amount of material in them, Newton called the attraction that of "gravitation." The general conclusion which he reached was that all bodies acted as if they were under an attraction for one another. He said:

Every particle of matter attracts every other particle with a force that is directly proportional to the product of their masses, and inversely proportional to the square of the distance between them. This is the famous Newtonian law of universal gravitation. It contains two distinct factors—one concerning the mass of the bodies, and the other the distance between them, and its author originally presented these two features separately. A sphere would act toward bodies external to it as if all its mass were concentrated at its center, and the distance between two spheres means the distance between their centers. A proof of the two parts of the law requires many experimental tests, but a few simple facts illustrate it in a striking manner.

HOW THE TWO PARTS OF THE LAW WERE ESTABLISHED

If a piece of lead, say one cubic inch, is dropped from a height to the earth, it undergoes a definite, measurable acceleration, and acquires a definite velocity; a piece twice as large (two cubic inches), has exactly double the mass of the first. Now if

the earth's attraction upon this is more than twice as great as upon the first, it will give the body a greater acceleration; if the force is less than twice as great, the acceleration will be less than at first. The acceleration or change of velocity cannot be the same unless the force is doubled when the mass is doubled, or trebled when the mass is trebled, or in general the force is proportional to the mass. It is for experiment to determine whether bodies of different mass have the same acceleration under the action of gravity; i.e., whether all bodies, heavy and light, fall at the same rate. Seventy years earlier Galileo had demonstrated this as a fact, in a thrilling experience at Pisa, where, before a crowd of incredulous spectators, he had dropped simultaneously a 100-pound ball and a 1-pound ball from the leaning tower. Even their striking the earth together did not convince the doubters. When feathers and bits of paper fell along with pieces of lead or iron, the difference was too palpable, and the means of getting rid of air resistance was not then available. Later, the familiar experiment of inclosing various objects in a long glass tube from which the air can be extracted, exhibited plainly enough the intimate companionship of the lead and the paper in falling from one end of the tube to the other. It is really impressive to see the swiftness with which the paper or feather darts down by the side of the metal, although before exhausting the air from the tube the paper saunters down very leisurely.

Newton's way of proving this was even more satisfactory. He had several hollow balls of the same size, suspended by strings of the same length, as pendulums. These spheres he filled with very different substances, metal, earth, and what not, and

set the pendulums swinging. No matter what their contents, they swung in unison, and as gravity was the only agent causing them to descend from their high to their low position, they were all accelerated precisely alike—something which could not happen unless the force of gravity upon each body was just in proportion to its mass. This experiment had the further merit of showing that gravitative action was quite independent of the nature of the material.

The proof of the law concerning distance was much more difficult, but if the law were correct the fact should be evidenced in the acceleration of the moon toward the earth to describe its orbit around the latter. An erroneous value for the distance from the earth to the moon delayed this proof for some years, but when it was finally shown that the moon does conform to the law, and that the law could be extended to all the heavenly bodies, the way was opened for immense strides in both astronomy and physics. Not until about 1800 was the law proved experimentally for the action of small masses upon each other at short distances. This was done by the English physicist, Henry Cavendish, in a famous experiment to measure the attraction of massive leaden balls upon small ones. As a result it is found that the mass of the earth is 6690×10^{18} tons (10^{18} is a billion of billions); or the earth is 5.527 times as heavy as a globe of water of the same size. In this way Cavendish is said to have "weighed the earth."

THE CENTER OF GRAVITY

The attraction of the earth upon bodies is directed, virtually, toward the center of the earth. The direction of attraction upon a body at the equator would be at right angles to that upon one at the pole, but

LILIENTHAL IN HIS GLIDER, 1896

Photo, A. N. Mirzaoff

THE AMERICAN AVIATOR ALLEN TAKING OFF IN HIS GLIDER AT COMBEGRASSE, FRANCE, 1922

for bodies of moderate size, or occupying a small territory, the lines of attraction (plumb lines) converge so slightly that they may be considered parallel, with no appreciable error. Even for bodies a mile distant from one another, the lines are at an angle of only one-sixtieth of a degree, and for large structures, the angle between plumb lines at different corners is too small to be taken into account.

The combined effect of parallel forces, that is, their resultant, is simply their sum, and the combined gravitative attraction of the earth upon all the individual particles of a body is the weight of the body.

Now it is shown in mechanics that when the parts of a body are impelled by parallel forces, *whether vertical, or horizontal, or in any other direction,* which forces in each particle are proportional to the mass of that particle, the entire set of forces might be replaced by a single force equal to their sum, and applied at a point definitely located with reference to the body. This point is called the center of the forces. Gravity is a special case in which the forces happen to be vertical, and their center is called the center of gravity of the body; and as regards any action external to it, the body may be considered as concentrated at its center of gravity.

A peculiarity of such a system of forces applied to the separate particles making up the body is that if the forces were turned about into any direction whatever, so long as they remain parallel, their resultant will pass through the same point or "center." What comes to the same thing is, that if the forces are continually in the same direction, as is the case with gravity, although the body be turned into any variety of positions, the action of gravity as a whole will still pass through the same point or center. If

it were to be counteracted by a single force, this must be in a line directly opposite to the force acting, so that against gravity it must be vertical. Accordingly, if a body be suspended by a thread, the direction of the thread passes through the center of gravity of the body, and if the body be again suspended by attaching the cord to it at another point, again the line of suspension, traced through the body, will pass through the center of gravity, and will intersect the former line in that point.

It is plain that under the influence of gravity, unless the body is held in a particular position it will move so as to permit the center of gravity to descend as far as possible; and moreover, if the body stands upon feet or rests upon a base in such form that a vertical line through the center of gravity passes outside of a line circumscribing the feet, or base, on which it stands, that body will topple over, and if the vertical passes within this circumscribing line it will stand. Alarming as the Leaning Tower of Pisa looks, so long as it does not violate this principle it is not in danger of falling.

This remarkable structure inclines thirteen feet from the vertical in a height of about 180 feet, and excites a decided feeling of apprehension in the beholder. This feeling is heightened in the visitor when he emerges from the interior upon the balcony at the seventh story, climbs upward along the footway around the tower on one side, and still worse as he descends on the other side. To add to its top-heaviness, in the upper chamber are mounted seven bells, of which one alone weighs six tons, yet the vertical line through the center of gravity of the entire structure passes well within the boundary of the base, and the position is stable.

To the physicist it is of more interest on account of its associations with Galileo than as the bell tower of the cathedral, for which it was erected.

In a symmetrical body of homogeneous material the center of gravity is at the geometrical center of the figure, though not necessarily within the material of which the body is composed. In a ring or hoop, for instance, the center of gravity is at the center of the ring. In a triangle it is on a median line of the triangle, at one-third the distance along that line, from the side to the vertex of the opposite angle.

THE WEIGHT OF A BODY VARIES WITH ITS SITUATION

The force with which a body is held to the earth by the attraction of the latter we call the weight of the body, and, as we have seen, the effect of centrifugal action is to make that force less at the equator than at the poles by 1/289 part. Owing to the spheroidal shape of the earth, the distance from the surface of the earth to the center is greater at the equator than at the poles by nearly thirteen miles; consequently the attraction, on that account, is less at the equator by about 1/550 part. These two effects combined make a body weigh less at the equator than at the pole by about 1/192 part, or a body weighing 192 pounds at the pole would weigh 191 pounds at the equator, with a corresponding difference at intermediate latitudes.

In the ordinary or "beam" balance with equal arms the "weights" are graded pieces of metal, the pound being one that exactly balances the standard pound, and the others, multiples or divisions of that. When one or more of these "weights" in one pan exactly balances an object in the other pan it is an evidence

that there is just as much mass in the object as in the weights, since gravity attracts them equally. This would be true, no matter where, upon the earth, the weighing were done, for the variation of gravity is the same on the weights as on the bodies to be weighed. If, however, a spring balance, like the dynamometer, be marked for pounds, by the standard weights at a given latitude, say the Bureau of Standards at Washington, the body which, according to the spring balance, weighed one pound at Washington, would weigh more than a pound on the same balance at London, where the attraction of gravity is greater by about 1/1000 part. It would pay to buy goods in Cuba with the beam balance and sell them in London by the spring balance.

In reality the beam balance compares masses, and the spring balance compares weights.

So sensitive and delicate can beam balances be made that they afford the most accurate of all means of comparing masses.

THE PRINCIPLE OF ARCHIMEDES; IRON MAY FLOAT IN WATER

The story of a great discovery always has something fascinating about it that perpetuates the fame of the achievement. One of the oldest as well as most noted stories in connection with the science of physics is that of the so-called *Principle of Archimedes*. The discovery is said to have come about in this wise: Hiero, King of Syracuse, to whom Archimedes was related, had ordered the preparation of a golden crown of a specified weight and fineness, for an offering to the gods. The crown was duly delivered, and was of the proper weight, and apparently according to order, but the suspicions of the

king had been aroused that the gold in it had been alloyed by mixture with a baser metal, probably silver. He knew no way to determine whether this was the case, and asked Archimedes to solve the difficulty for him. With the matter continually in mind, the philosopher was pondering over it one day as he went to a bath. The bath vessel was full to the brim, and as his body sank more and more deeply into it, more and more water overflowed. If entirely submerged, plainly a volume of water equal to his own bulk would be displaced. Moreover, he was necessarily conscious of greater buoyancy as he sank farther into the fluid. Then came to him a perception of the displacement of liquid by a floating body, one that would only sink far enough, and displace enough liquid to have its whole weight supported—and the solution of his problem flashed upon him. According to the story he was so elated that he leaped out of the vessel in joy, and returning home cried out with a loud voice, "Eureka! Eureka!" (I have found it! I have found it!) Just what the idea was that so pleased Archimedes may not flash promptly upon the mind of every reader, but he proceeded to apply it by immersing in a vessel full of water, first the crown, observing the volume of water displaced; then an equal weight of gold, which, he found, displaced less water (i.e., had smaller volume)—and finally the same weight of silver, which displaced more water than the crown. Thus it became evident that the crown was not wholly of gold, but was probably made of gold and silver mixed.

The "principle" which Archimedes was soon able to formulate is that a body partially or wholly immersed in a liquid is buoyed up with a force equal to the weight of the liquid it displaces. If the body

is lighter than its bulk of water, it sinks until it displaces a volume of water that equals itself in weight, and then it floats; if it is heavier than its bulk of water, it sinks under the water, but still loses weight equal to the weight of its own volume of water. The all-important thing, the essence of the principle, and the idea that so stimulated the great philosopher, is that the buoyant action of the liquid is equal to the weight of the liquid that is displaced by the body, no matter what its own form or material may be.

A solid iron cube, three inches on a side, weighing 6.8 pounds, would sink in water, and when under water it would not equal the weight of 6.8 pounds in the other pan of the balance out of the water, but would weigh less by very nearly one pound, that being the weight of its volume (27 cubic inches) of water.

The same amount of iron in a sheet one-fiftieth of an inch thick could be made into a cylindrical vessel like a huge can, 24 inches long and 15 inches in diameter, weighing just as much as the solid cube. But this vessel, placed upright in water, not only would not sink, but would float with a cargo in it of 153 pounds before its edge came to the level of the water. Thus the feasibility of an iron boat was established before the Christian era, though it remained for the nineteenth century to put it into practice, and verify the apparently absurd and impossible prediction in Mother Shipton's famous (though spurious) prophecy:

"Iron in the water shall float
As easy as a wooden boat."

To-day the wooden ship has almost wholly given place to ships of iron and steel, or even of concrete.

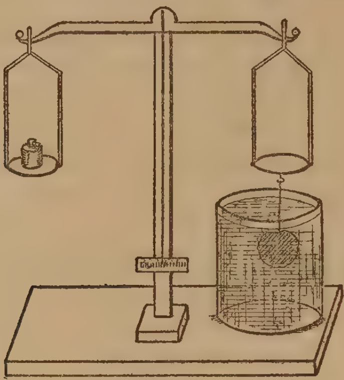
If the iron cylinder just described were sealed shut at both ends, it would be buoyed up by a force of 153 pounds when submerged in water, or, in terms of weight, would lose more than it possessed!

While it is a common laboratory exercise for students to test the principle of Archimedes by having a vessel full of water, and immersing in it a body of known size, catching the water that overflows and weighing it; or by putting in a body that floats and comparing the weight of the displaced liquid with the weight of the body, the principle, when established, can be used without a vessel filled to overflowing. By suspending a body from an arm of a balance, weighing it and then immersing it in a liquid and observing its loss of weight, which is simply the weight that has to be taken from the pan containing the counterpoise, to restore the balance when it is buoyed up by the liquid, the weight of its volume of the liquid becomes at once known.

THE SUBMARINE BOAT

A boat constructed on the principle described above may be made to sink or float at will, and that is just what is done in the case of the modern submarine. The lower part of the hold is divided by partitions or "bulkheads" into numerous compartments that are water-tight but communicate with the sea outside by cocks through which water may be admitted or expelled. With these chambers full of water, the ship with its equipment sinks until it is nearly but not quite submerged. In earlier forms the compartments were of such capacity that when filled with water the ship's displacement was so reduced that the buoyancy was not equal to the weight of the boat, and it sank. It would remain

submerged until more water was displaced, which was accomplished by driving out the water from one or more of the chambers. This was done by admitting into them air under great pressure, from tanks containing air compressed into small bulk, but upon failure in the supply of compressed air, or a break



BUOYANCY

Determining buoyancy or loss of weight by a body immersed in a liquid.

down in the mechanism, the vessel would fail to rise again to the surface and disaster would result. So the water-air chambers now serve only to control the height at which the vessel rides. When they are filled with water the deck is nearly awash, and then, with the engines driving the ship forward, it is steered downward and made to dive by a horizontal rudder, just as a vertical rudder directs it to right or left. By filling or emptying compartments in different parts of the hold, fore and aft, the vessel is "trimmed" or balanced. The displacement of water being greater than the weight of the ship, when the driving stops and the rudder is no longer effective,

the ship rises again to the surface, and with further expulsion of water ("displacement"), it rises still higher and deck operations become possible.

BALLOONS; THE "DIRIGIBLE"

When it was realized that air had weight and exerted a buoyant effort upon bodies immersed in it, just as water does, it was found that the principle of Archimedes applied to it also, and as hot air was lighter than cold air, balloons were made in which the air was kept heated and they would rise. Such were the earliest balloons, and ascensions in them have been made in very recent times. The upward force of the air is always equal to the weight of the air the balloon displaces. Later, when other gases were discovered that were much lighter than air, they were used to inflate the balloons; this did not make the lifting force of the air greater for the same sized balloon, but made it possible to construct larger balloons without greatly increasing their own weight.

In consequence of the extraordinary possibilities it offered for invasion and operations of offense, the balloon was rapidly developed during the late war. It reached its acme of achievement, however, after the war when, in July, 1918, the British *R*-34 crossed the Atlantic from Scotland to America and returned —a nonstop flight each way. This enormous craft displaces two million cubic feet of air. As air at the earth's surface and a temperature of 32° F. weighs 0.08 of a pound per cubic foot, this would give the dirigible a lifting force of 160,000 pounds. The weight of the airship with its machinery and fuel is 130,000 pounds, and this would leave a possibility of carrying nearly fifteen tons of passengers or cargo when near the earth. At three and a half miles

elevation, however, the air is only one-half as dense as at the surface of the earth, and therefore the buoyancy would not be sufficient to float the ship at that height. It could rise to a height of 14,000 feet if inflated with hydrogen. It is a slow and expensive process to produce hydrogen on such a scale, and this, like illuminating gas, is inflammable and is therefore a source of one of the gravest dangers that threaten the balloon, namely, fire; for the dirigible employs a combustion engine to drive it. It is now known, however, that helium gas can be obtained in large quantities from oil wells in Texas, and as this gas is only about twice as heavy as hydrogen, its addition to the gross weight of the airship is not excessive and there are large possibilities of advantage in its use in aeronautics.

CHAPTER XIV

SPECIFIC GRAVITY—DENSITY

THAT bodies of the same size differ in weight is plain without taking the trouble to compare them on an exact balance. The term gravity applied to bodies in general means literally their heaviness or weight, but when applied to any substance specifically, it means the weight of any portion of the substance, as compared with the weight of an equal volume of some other substance, taken as a standard for comparison, and is called its "specific gravity." In that way the term specific is used throughout physics to express various qualities or properties besides weight, as "specific heat," "specific resistance," etc.

Owing to its commonness in nature and the ease with which it can be manipulated, water has been adopted as a standard substance with which to compare bodies of other kinds, especially in a liquid or solid form, and when the specific gravity of any substance is mentioned it usually means the weight of any body of that substance as compared with the weight of an equal volume of water. As a piece of iron of any size is 7.8 times as heavy as its volume of water, the sp. gr. of iron is 7.8; as a piece of cork weighs only .24 as much as its bulk of water, its sp. gr. is 0.24; if the weight of the turpentine necessary to fill a bottle is 0.87 as much as the weight of water required to fill the same bottle, the sp. gr. of

turpentine is 0.87; always an abstract number—the ratio of the weight of the body to the weight of an equal volume of water.

Why a body of one substance should weigh more than one of the same size of another substance we do not know, but the fact that it does so, taken with the law of gravitation, leads us to conclude that one has more matter in it than the other, or, technically, has a greater mass. The term to express the mass of a body in comparison with its volume is "density." Sometimes density is thought to indicate the closeness to one another with which the particles are packed in a body. That would be true of two different specimens of the same material if the substance could be squeezed into a smaller or swelled into a larger volume, but it would not necessarily be true in comparing the density of two different substances. We shall see later that, with the same number of molecules of the two gases oxygen and hydrogen in a cubic inch, and with no reason to suppose that the molecule of one differs greatly from that of the other in size, and therefore with no great difference in the closeness of the molecules, nevertheless the cubic inch of oxygen weighs about sixteen times as much as that of hydrogen, or has sixteen times as much mass in the same volume, and oxygen is therefore sixteen times as dense as hydrogen.

Density, therefore, or more strictly absolute density, means mass per unit volume. The number of units of mass in a body, be they pounds or grams, divided by the number of units of volume in the same body, cubic inches, or cubic centimeters, will give the number of units of mass in one unit of volume, and that is the absolute density of the substance composing the body. It is never an abstract number; what

the numerical value is will depend upon the units in which both mass and volume are expressed, but both of these terms should be named in expressing the absolute density. Iron has 0.28 pounds in a cubic inch, and 7.8 grams in a cubic centimeter, and either of these is a correct value of the density of iron; but its specific gravity is once and only, 7.8.

The "specific density" of a body is its density in comparison with that of a standard substance, which, again, for solids and liquids is usually water. This, like specific gravity, is simply a number; the mass per unit volume being such a number of times (large, or small, or fractional) as great as that of water.

Here the advantages of the c.g.s. units become considerable. In that system the mass of one cubic centimeter of water is one gram, and therefore the number of grams per cubic centimeter of any substance is at the same time the number expressing its absolute density, its specific density, and its specific gravity.

Numerous ways have been employed to determine density or specific gravity, the description of which belongs rather to the physics laboratory, but one or two of the simplest may not be out of place here. For specific gravity the whole problem consists in weighing a body in air, and then finding how much an equal volume of water weighs. If the body is heavier than water, and not soluble in it, the method previously described (p. 105) tells the loss of weight of the body in water and that is the desired weight of water equal in volume to the body: therefore the specific gravity is the weight in air divided by the loss of weight in water. If the substance is lighter than water, a sinker whose loss of weight in water

has been previously determined, is attached to the body, and then the loss of weight of the two combined is found. Subtracting from this the loss by the sinker, the remainder is the loss by the light body, and its weight in air, divided by this loss, is its specific gravity. This latter "loss" will be found to be more than the actual weight of the body in air, so that the specific gravity will be a proper fraction, or less than unity:—with a piece of cork it will be found to be only from 0.18 to 0.25.

For a liquid, a heavy solid not acted on by water or the liquid, is weighed in air and in water, the difference being the weight of its volume of water: then when weighed in the liquid, its weight here, subtracted from that in air, is the weight of its volume of the liquid, and the ratio of these two is the specific gravity. A piece of coal, taken at haphazard, weighed 2,000 grains in air, 823 grains in water, and 1,030 grains in alcohol. Its loss in water was 1,177 grains, and in alcohol 964 grains, the specific gravity of alcohol was $\frac{964}{1177}$ or 0.82. Incidentally this gives the specific gravity of the coal, the weight in air divided by the loss in water, as $\frac{2000}{1177}$ or 1.7.

For density, if the same substance is used for comparison as for specific gravity, then specific gravity and specific density will be the same number. The absolute density is most commonly expressed as pounds per cubic foot or grams per cubic centimeter, and with water as the standard, any plan of weighing or measuring that will tell the number of grams in a cubic centimeter gives at once the same numerical value for the specific gravity, the specific density, and the absolute density in grams per cubic centimeter. In the general science of physics, the last

named quantity is of more service than either of the others.

Of all solid substances, platinum is the densest, containing 21.5 grams per cubic centimeter; gold has 19.32; lead, 11.36; copper, 8.94; aluminum, 2.65. Of liquids, the density of water is 1 gram per cubic centimeter; mercury, 13.6; ether, 0.736. Of gases at 0° C. and 760 cubic millimeters pressure, air has .001293 grams per cubic centimeter; ammonia, .000771; hydrogen, .0000898; helium, .000177; steam (100° C.), .000596.

HYDROMETERS

A light rod or tube, slightly weighted at the lower end, will float upright, sinking in different liquids to various depths, depending upon the specific gravity or density of the liquid. If it is graduated by being placed in several liquids of known density, a scale may be made on it, which will show the density of any liquid in which it may be placed. Such an instrument is a hydrometer. Water is marked 1,000, and all readings should be divided by 1,000 for the specific gravity or the specific density.

Various scales are in use to adapt the instrument to the particular purpose it is to serve. As an alcoholometer it will show the percentage of alcohol in a sample of beer or wine; as a lactometer it shows the proportion of water added to rich milk to reduce its specific gravity to the smallest figure allowed for inspection. When the automobile dealer, therefore, instructs his customer that the acid in his storage battery must show a stated hydrometer reading, the user must be careful to understand what hydrometer scale is meant—knowledge which the salesman himself does not always possess.

CHAPTER XV

LIQUIDS AND GASES

EVANGELISTA TORRICELLI (1608-1647), a pupil of Galileo, had succeeded in 1643 in producing a better vacuum than had been obtained before, but how to explain the standing up of the column of mercury nobody knew. That air had weight, or exerted any pressure when not in motion, was a strange idea. Other investigators followed up Torricelli's work, among them being a brilliant young French physicist, Blaise Pascal (1623-1662). He at first ascribed the column of mercury to Nature's *horror vacui*, but learning soon after of Torricelli's experiments with air pressure, he began to suspect that the explanation of the barometer column was somehow connected with that—maybe was due to the weight of the air outside the tube. In November, 1647, he wrote to his brother-in-law, Perier, in Clermont: "You see, if the height of the mercury column is less on the top of a mountain than at the foot of it (as I have many reasons for believing, although everyone who has so far written about it is of the contrary opinion), it follows that the weight of the air must be the sole cause of the phenomenon, and not that abhorrence of a vacuum, since it is obvious that at the foot of the mountain there is more air to have weight than at the summit, and we cannot possibly say that the air at the foot of the mountain has a greater aversion to empty space than at the top."

To carry out Pascal's suggestions, Perier prepared two barometers, and on September 19, 1648, leaving one in charge of Father Chastin in Clermont, he carried the other up the Puy-de-Dôme, a neighboring mountain something over 4,000 feet high.

As he ascended the mountain the barometer column fell steadily, and when, after the expedition, the height of the barometer at the foot of the mountain was compared with that at the top at the same time, the difference was found to be a little more than three inches.

Perier at once informed Pascal of the success of the experiment, and the latter was astounded by the great difference in the height of the mercury; an inch or even half an inch would have seemed to him strong support of his ideas, but a difference of more than one-tenth of the whole column was overwhelming! He now extended his experiments by employing other liquids than mercury, especially water, and spirits of wine. These required very long tubes, and he had recourse to the tower of the church of St. Jacques de la Boucherie, in Paris. He found that the other liquids all stood at heights greater in proportion as their density was smaller, so that in every case the pressure exerted at the base was exactly the weight of a column of the observed height—mercury with a height of 30 inches, water, 13.6 times, and wine, 17 times as high. Exactly the same weight of liquid of every kind was sustained, and the conclusion was irresistible that it was the pressure due to the weight of the air outside of the tube that counterbalanced the liquid inside of it, and the horror of a vacuum had nothing to do with it. This was the first actual proof of the weight of the atmosphere, and now, for the first time, it was possible to explain

rationally not only the action of the barometer, but also that of the common suction and lifting pump.

One of the most astonishing facts revealed by Von Guericke's experiments with the air pump was not that the air exerted pressure, but that it had weight. But Pascal's experiments with the various liquids were made before the air pump was invented. These showed that the pressure per square inch at the base of a barometric column of water was exactly equal to the weight of a column of water one square inch in cross section and thirty-four feet high; the pressure per square inch at the foot of the mercury tube was equal to the weight of a column of mercury one square inch in area and thirty inches high, and so on. The inference was plain that the pressure of the atmosphere per square inch was equal to the weight of a column of air on a base of one square inch and extending to the top of the atmosphere.

How far that was nobody knew, but as this weight amounted to 14.7 pounds, and the weight of a definite quantity of air at the earth was now known to be about .00004674 per cubic inch, or that a column on a base of one square inch and one foot high would weigh .00056 pounds, it was easily calculable that to weigh 14.7 pounds would require a column of 26,200 feet in height, or just about five miles. As it was well understood that the air grew less dense at the increasing altitudes, its upper limit was necessarily much higher than this; how much higher was not known.

Pressure of a liquid is independent of the quantity, and of the shape of the vessel; it depends only upon the depth.

Pascal's further experiments brought to light many truths concerning fluid pressure.

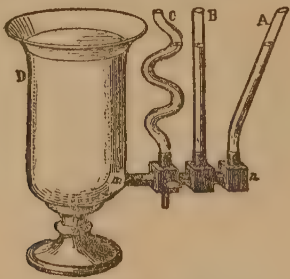
At any point in a fluid at rest, pressure is equal in all directions. This needs no proof, for in a fluid the particles are free to move, and if, at any point, a particle were pressed harder in one direction than in the opposite direction it would move, and the fluid would not be at rest.

In a cubical vessel, one foot on each side filled with a liquid, say water, the weight of the cubic foot of water, 62.4 pounds, presses upon the bottom. The pressure is 62.4 pounds to the square foot and that is the intensity of pressure at every point of the bottom. Upon any layer above the bottom the pressure is the weight of the column above it, so that at any depth the pressure is proportional to the depth; but at a point where the side joins the bottom, the pressure outward against the side is just as great as the pressure downward, and is also 62.4 pounds per square foot, and this would be true, no matter what the shape of the vessel or of the superincumbent column of liquid.

There are many ways of showing that the pressure of a column of liquid due to the action of gravity is determined solely by the height of the column, but the simplest evidence is the fact that a liquid stands at the same height in communicating vessels, no matter what their form may be. If vessels of various shapes communicate with one another at their bases, a liquid will rise to the same height in them all. Compare the pressure on a particle between the bases of the vessels C and D. The slender column of liquid in C exerts a pressure to drive the particle to the left; the broad column in D pushes it to the right. As it is at rest, or moves neither to the right nor the left, the pressure upon it is equal in both directions.

Thus the pressure tending to rupture a vessel or a reservoir is dependent only on the depth of liquid and not upon the quantity. Suppose we have a cask, one foot in height, and one square foot in area of cross section.

When filled with water it has a weight of 62.4 pounds on its bottom and sustains a pressure of 62.4 pounds per square foot, or nearly half a pound to the square inch, outward at the base, tending to burst



PRESSURE OF LIQUIDS

Pressure of liquid is independent of the form of the vessel containing it.

the cask. If the vessel were taller and of the same width, the weight of the liquid resting on the base would be increased by the same amount for every additional foot of height in the liquid column. Filling up the vessel would be like piling up a column of bricks. But in the case of the liquid, the lateral pressure everywhere is the same as the vertical. At thirty feet high, the pressure would become thirty times 62.4, or 1,872 pounds per square foot, and, unless the cask were exceptionally strong, it would burst. But as we have just seen, the same effect of pressure would result if the column of liquid were not so wide as the base; indeed, if it were no larger

than a pipe stem. The danger from rupture would be as great from the narrow column as if it were of full width to the top.

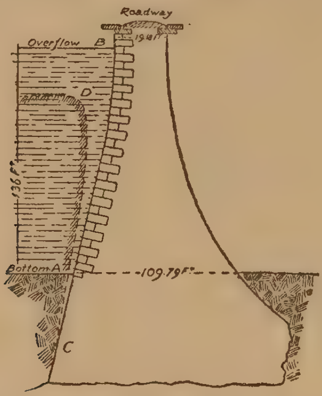
We can see how it is that a thin, narrow tube will safely carry a high pressure of steam (or water) from a boiler to a cylinder. If the internal diameter of the pipe were half an inch, and the pressure were 100 pounds per square inch, one foot of length of the narrow pipe would only have a total pressure of 600 pounds to tear the metal asunder, and thin walls of tubing could stand it; but on the same length of a boiler two feet in diameter, the force to produce rupture would be 48 times as great, or more than 14 tons, and it must be made thicker and stronger; so, too, must the cylinder, if only one foot in diameter, as it is subject to sudden and severe changes of pressure.

The figure on the next page shows the Croton Dam of the New York City water system in profile. When the dam is full to overflowing, the water has a depth of 136 feet, the pressure is great, and the quantity of water stored is enormous. But observe that the pressure against the dam is not determined by the quantity of water. If the dam were filled up with earth to the height indicated by the broken line and light shading, but ever so narrow a space permitted the water to continue down along the wall, say to C, below the present bottom A, the water pressure against the wall would be greater than at present—as great, in fact, as if the entire depth BC extended upstream indefinitely.

BAROMETERS—BAROMETRIC PRESSURE

While the Torricellian barometer can be easily prepared, the standard barometer, known as Fortin's, has to be carefully constructed and graduated.

The mercury is boiled to expel all air from it, and the glass tube, as well as the cistern of mercury into which the lower end of the tube dips, is incased in metal. From the top of the larger portion of this case, inclosing the cistern, an ivory point projects downward, and a screw in the bottom of the case makes it possible to bring the surface of the mercury in the cistern just into contact with the ivory point. This is the zero of the scale. The top of the column is

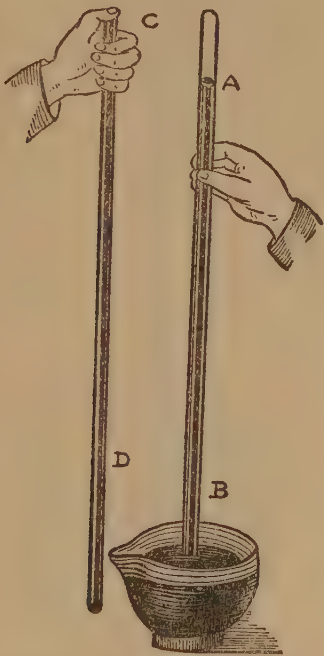


PRESSURE ON A DAM

Danger of failure in a dam is not determined by quantity of water.

determined by a sliding metal collar whose upper edge is brought into the same plane with the top of the mercury in the glass tube. The side of this metal collar is a vernier scale matched against the scale of inches (or centimeters) on the metal tube incasing the glass, by which the length of the mercury column can be read to 0.002 of an inch. So sensitive is the instrument that it will readily show a difference of atmospheric pressure on successive floors of an ordinary building.

The height of the barometer column is constantly changing under changing atmospheric conditions, and on that account the barometer is the most valuable of means for making meteorological observations. As with all other measures, some value has to



TORRICELLI'S BAROMETER TUBE

be chosen as a standard on which to base comparisons. The English standard for an atmosphere is a column of mercury 30 inches high, at a temperature of 62° F., at sea level, in latitude 45°. All these conditions have to be mentioned because a change of any one of them in a given column of mercury would alter its weight, and consequently the same height of

barometer column would not always mean the same pressure of the atmosphere to sustain it. The effect of gravity in producing the weight of a body varies slightly, as we have seen, with the latitude, and also with the elevation or distance from the center of the

THE STANDARD BAROMETER

earth, and a definite weight of mercury in a narrow tube will be longer or shorter, depending on these facts and on its temperature. For these reasons, in accurate uses of the barometer, whatever the actual scale reading of the barometer column may be, such corrections must be made as to give the length of column to which the observed value would reduce

under the above standard conditions. These corrections in ordinary cases are not large, in most instances not more than a few thousandths of the observed reading.

The standard barometer column in metric units has a height of 760 millimeters at the temperature of melting ice, at sea level, in latitude 45°. This gives an actual pressure of 1,013,250 dynes or 1033.3 grams per square centimeter, or 14.69 pounds per square inch. Sometimes the even number 1,000,000 dynes per square centimeter is taken as "an atmosphere," and is called a "megabar."

A more convenient and portable form of barometer is the aneroid. (The name means without moisture.) This is a case of sheet metal whose front is very thin

ANEROID BAROMETER

and corrugated, making it at once strong and flexible. The box is partially exhausted of air, and sealed shut. Except in very rare air, then, the face is always under pressure inward, yet sensitive to very slight changes in the pressure upon it. The flexible front yields outward or inward with any such change, and by an attachment of levers at its center

its movement is amplified, and the end of a pointer is moved over a scale. This is graduated to read the inches of mercury column in a standard barometer corresponding to the pressure, or, frequently, in feet corresponding to the height above the earth at which the atmospheric pressure would correspond to the indication of the barometer: An instrument of this kind is of especial service to explorers, particularly in determining mountain heights; and with the progress of aeronautics, it has become an indispensable feature in the outfit of the aviator, by which he knows the height at which he is flying.

The density and therefore the weight of air depends upon its temperature as well as its pressure, but a single table will serve to show how the barometer pressure varies with the height above sea level. If the mean temperature of the air between sea level and the highest point reached is, say, 50° F., as it would be if it were 70° at sea level and 30° at the upper level, the following table gives the elevation for the barometer reading in inches of mercury column and also in pounds per square inch.

Barometer Pressure		
Lbs. per sq. in.	Inches of mercury col.	Elevation in ft. above sea level
14.7	30.	0.
14.17	28.92	1,000
13.66	27.88	2,000
13.16	26.86	3,000
12.69	25.90	4,000
12.23	24.96	5,000
12.1	24.70	5,280
11.78	24.04	6,000
11.36	23.19	7,000
10.95	21.35	8,000
10.55	21.53	9,000
10.17	20.36	10,000
9.28	18.94	12,500
8.46	17.26	15,000
7.44	15.18	3½ miles

These figures would be somewhat different, though not greatly so, for other temperatures. If the mean temperature of the air between the sea level and the highest elevation were 20° F. instead of 50°, the barometer pressure at the height of one mile would be 11.96 pounds per square inch, instead of 12.1, and the mercury column would be 24.41 inches, instead of 24.70; at 3½ miles, 7.14 pounds per square inch, and 14.63 inches height of mercury column.

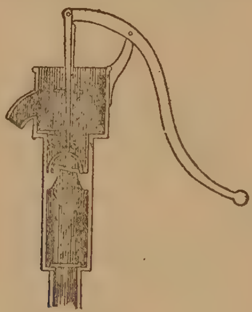
BOYLE'S LAW

A fever of investigation of liquids and gases prevailed among scientists in the second half of the seventeenth century. Robert Boyle (1627-1691) was among the earliest experimenters upon the properties of air, and deduced from his experiments one of the simplest yet most important laws concerning gases, which he announced in 1662.

This famous law, which was afterward to prove fruitful in many lines of investigation, though originally determined for air only, is now extended to all gases, and is known simply as "Boyle's Law." It is, "If the temperature is constant, the volume of a given mass of gas will vary inversely as the pressure it exerts." By varying inversely is meant that if a definite quantity of a gas at, say, atmospheric pressure is shut in a vessel, one side of which could be pushed in like a piston, when an additional pressure of 14.7 pounds per square inch is applied to this piston, the gas will be compressed to one-half its volume; if the pressure is made three times as great the volume becomes only one-third. On the other hand, if the vessel can be opened to communicate with another of the same volume, it will share its contents with this; and the original gas will now occupy twice

the original volume and will exert only one-half as great pressure. In such a relation, the product of the volume by the pressure is a constant number.

The action of the common pump is an application of Boyle's law. The column of water in the pipe can be supported only to a height above the level of the water in the well, at which its pressure is as great as that of the atmosphere, or about 34 feet.



SUCTION AND LIFTING PUMP

An application of Boyle's law.

Hence the upper valve must not be more than 34 feet above the level of the water in the well. After the water passes above this valve, the piston dips into it and is all the better sealed thereby, and any depth of water above it is lifted bodily by the lever action of the pump handle; so the depth from the outlet to the upper valve may be as great as we please. The pump is a complete example of atmospheric pressure and of Boyle's law, which the ancients had long practiced unwittingly.

THE AIR PUMP

Air and other gases, if inclosed, may be treated in many respects like liquids. Many principles, such

as that of Archimedes and the transmission of pressure, apply to fluids generally, gases as well as liquids. The pump just described will draw air or gas from a closed vessel precisely as it draws water from a cistern, the air that remains in the vessel after each stroke being always of the volume of the vessel containing it, but always diminished in pressure, if the working piston is air-tight.

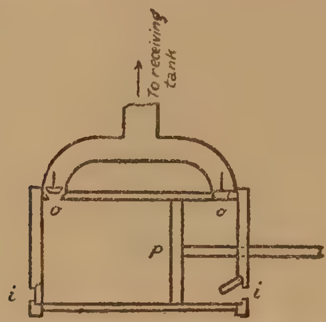
In the driving action of the propeller upon the ship or the airplane, if the vessel does not move, the air or water is driven at a high speed, *from* the propeller on one side, and *to* it, and *through* it, from the other side. If this other side is a closed pipe leading from a reservoir, the propeller becomes a pump drawing out the fluid in the reservoir. When thus applied to an air chamber it is called a vacuum machine, and in this we have another recent application of science to domestic uses. The little electric motor of the vacuum cleaner, driven at a high speed, has on its shaft a propeller inclosed in a chamber, of which one outlet communicates with the surface of the carpet or rug covered by the machine, and that on the other side leads into a large receptacle as a sack. On the vacuum side of the propeller, dust and small light particles are drawn out and carried by the draught into the sack. The appliance is highly scientific, yet so simplified that "a child can operate it."

Air pumps have been improved by special devices to prevent leakage. It is possible now to reduce the pressure of gas in a vessel far below one-billionth of an atmosphere.

Of perhaps even greater importance in the arts is the reverse operation, that of compressing air by forcing it into a vessel or chamber. For this a force pump or compressor is used.

THE AIR COMPRESSOR

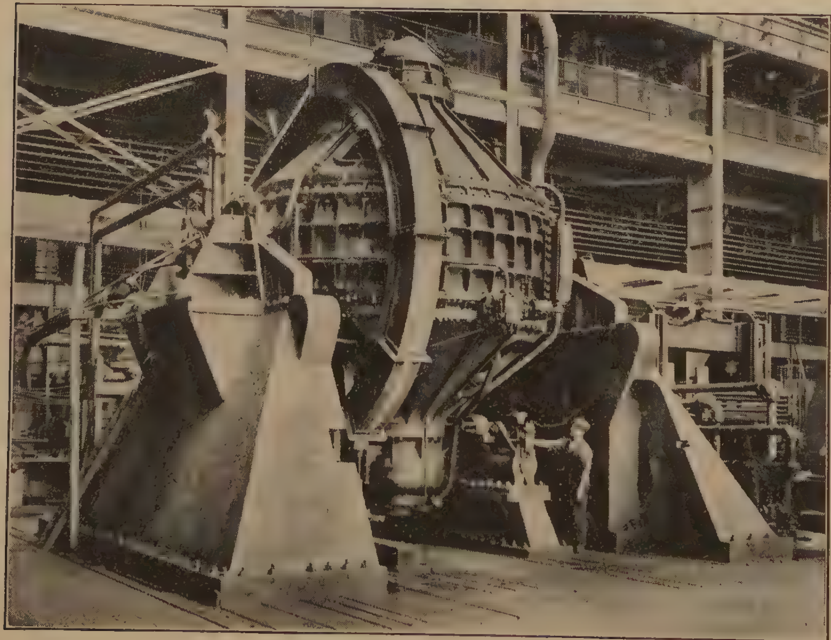
The action of the air compressor is shown diagrammatically in the figure below. A piston, P, without valves, is driven back and forth in a cylinder, by a hand lever, or more commonly by some sort of an engine. At each end of the cylinder is a valve, i, opening inward, to admit air from the outside, and



CYLINDER OF AN AIR COMPRESSOR

The air compressor has a great variety of uses of vast importance in science and industry.

another, o, opening outward into a pipe that leads to the chamber into which the air is to be forced. In the figure the piston is supposed to be moving to the left; the inlet valve at the right is open and that at the left is closed. The outlet valve on the intake side of the piston is closed, and the pressure of air on the other face of the piston forces the air through the outlet valve at the left. At the end of the stroke, the cylinder is full of air at the atmospheric pressure, and on the return of the piston the inlet valve on the forward side is closed, and the air is driven through the outlet valve to a receiving tank. As air is greatly heated when severely com-



HUGE GYROSCOPE

MEN AT WORK IN A CAISSON CHAMBER, EMPLOYED IN THE CONSTRUCTION OF AN EAST RIVER BRIDGE

pressed, such machines are usually jacketed by cold water that is kept circulating around the cylinder. Compressed air, when used in submarine work, as caisson sinking, must have a pressure of about fifteen pounds per square inch above that of the atmosphere for every thirty-four feet of depth, so that men working in chambers one hundred feet beneath the water surface are under a pressure of four atmospheres.

The applications of compressed air for power purposes are many and varied. In tunnels, mines, or other places where escaping steam is objectionable, or the possible spark of an electric machine threatens danger, the drilling and channeling is done largely by compressed air, and even in outdoor rock drilling and quarrying the air drill is in constant use. Smaller tools are even more common. The nerve-racking clatter of steel construction—whether it be upon the frame of a skyscraper, the hull of a ship, or boilers for power and heating—is due to rapid blows of the compressed air riveter, by which one operator can do the work that would require ten or a dozen, hammering by hand. The same type of tool, fitted with a chisel, will literally carve stone into any artistic shape; and in mine haulage compressed air is applied to the propulsion of locomotives; more—it not only moves cars but stops them also. The air brake on railroad trains has completely done away with reliance on man power. By it a long train of cars at high speed and facing disaster may be brought to a stop before a brakeman on the rear car could receive the signal and apply his brake by hand.

In another use of compressed air, the air is carried through a hose which has a side connection with a vessel containing sharp sand. This sand is drawn along by the air and discharged with it from a

nozzle. This is a "sand blast." When the sand is directed against a hard surface it has a sharp abrasive and scouring action. In this way it is extensively and effectively used in foundries for removing scale and dirt from castings. Applied to large structures of stone, or of metal covered with paint, it is an excellent means of cleaning and renovating the surface. A glass surface is covered with paper that is stenciled in intricate patterns, and when subjected to the sand blast the pattern is quickly and perfectly "ground" upon the glass. With liquids instead of sand, this method applies a coat of paint very rapidly, on a scale such as the buildings of a World's Fair—and again it can be used so delicately as to tint or shade maps and drawings exquisitely.

With driven wells in which water does not rise to the surface, instead of installing a mechanical pump to raise the water, an "air lift" is often employed. This is simply a small pipe within the larger one of the well, or beside it, through which air under high pressure is discharged into the well at the bottom. The air rises in bubbles or pistons, raising the water and discharging it in a flow as abundant as the well can supply.

Pneumatic tube service is used extensively for handling mail in large cities, while the systems of pipes and carriers in department stores for sending money to a cashier and returning change are so familiar as to have become commonplace.

When the reservoirs for the water supply of a large city have been constructed, the great dams erected, and the water impounded for delivery, safeguards must be employed to insure its purity and wholesomeness. Filtration serves in part, but if the water is stagnant for some time it becomes stale or dead,

and requires aeration. Compressed air is distributed and discharged under the water, stirring it and mixing with it thoroughly, and giving it life and sparkle.

THE KINETIC THEORY OF MATTER

The remarkable spread of odors from a small portion of substance, as musk, for instance, or burning sulphur, has always excited attention, and with the discovery and recognition of various gases came the evidence that these diffused themselves among one another very freely. Then it became known that two different liquids with a common surface of contact would also gradually intermingle; if a vessel contains a heavy solution of copper sulphate in its lower portion, and water, which is lighter, rests upon that, after standing for some time quite undisturbed, it will be found that the heavier substance has risen in place of the lighter, and a gradual mixing is going on.

These phenomena helped to establish the theory that in gases and liquids the molecules are in continual motion among themselves. It was easy to extend the idea to solids; the only qualification needed was that in solids there are bonds of some sort that hold the molecules within a limited sphere of mobility; that in liquids these bonds are more relaxed and the molecules can move more freely, while still held within their influence upon each other; and in gases the range and vigor of their movements are so great as to carry them beyond the bounds of restraint; in consequence they move away as far as the confining vessel or other constraint will permit.

This is in essence the "Kinetic Theory of Matter." The same substance at first in a solid form, as ice, may have such energy of motion imparted to its

molecules as to bring it to a liquid state, as water, and, with sufficient further accession of energy, this may be changed to the gaseous state, as steam.

The molecular energy of a gas reveals itself in the character of pressure and temperature. The latter we may consider under the subject of heat.

WHAT CAUSES THE PRESSURE OF A GAS?

As a matter of fact there is no evidence that a gas does exert pressure until there is some surface for it to press against. That there is constantly a state of pressure everywhere in the atmosphere was long regarded as an absurdity, and not until a confined portion of air could have the air surrounding it removed could the idea appear other than absurd. Even now it is very impressive to see a membranous sack containing air expand under the receiver of an air pump, without the application of any force to it, and presently explode violently.

To account for the pressure of a gas it has been explained already that a change of energy means the exertion of force, and that the force may be measured by the change of energy per unit of distance which the body travels while its energy is being altered.

The molecules of a gas are sometimes likened to a swarm of bees or gnats, bunched as they are often seen, and flying about among one another promiscuously. The molecules, however, lacking any guiding instinct, may be supposed at times to come into collision at any angle and rebound in any direction; moreover, the space between them is very large compared to the size of the molecules themselves. Consider such a swarm of molecules in a cubical box. They incessantly strike against the walls of

the chamber and rebound and their velocity is reversed. A change of velocity is a change of kinetic energy. This occurs against one side of the box as often as one-third of the molecules go the distance necessary to cross from one side of the box to the opposite side, for one-third of the entire motion may be regarded as, say, right and left, one-third up and down, and one-third to and fro. This change of kinetic energy is the pressure.

A mathematical analysis of the motions along with the observed pressure and the measured density of the gas enables us not only to account for the relation of volume and pressure given in Boyle's law, but to account for change of pressure and volume by heat, and also to determine the actual velocity with which the molecules are moving; it shows that any two gases having the same temperature, pressure, and volume contain the same number of molecules, and although nobody has ever seen a molecule apart from other molecules, the kinetic theory aids in the interpretation of many occurrences in physics. Without going through the calculations, the actual average velocity of the molecules of several gases, at the temperature of melting ice and standard barometer pressure, is as follows:

Hydrogen	185,000 cms. per sec.	or	6,070 ft. per sec.
Oxygen	46,500 " "	"	1,525 " "
Air	48,700 " "	"	1,600 " "
Helium	132,100 " "	"	4,336 " "

CHAPTER XVI

HEAT AND TEMPERATURE

ON an embankment of a newly constructed railroad, unsheltered from frost or sun, steel rails were laid in early summer, and carefully set to a proper gauge. Within a month or two trains were in operation and travel and traffic were carried on with no thought of especial danger. Under a blazing sun a wreck occurred with serious injury and loss, and inspection revealed the fact that, within a few hours, the two lines of steel had spread apart and the train was derailed. Sufficient care had not been taken to provide for the expansion of the rails, caused by rapid and extreme heating, and as the resistance to movement was greater lengthwise than laterally, two opposite rails bowed outward and the accident followed. The extremes of temperature to which the rails were exposed between day and night would have made a difference of a quarter of an inch in the length of one rail, and if several successive rails were jammed firmly against one another at their ends, the spreading effect, occurring where a rail or its attachment to the ties was weak, might readily lead to disaster.

A blacksmith welds together the ends of a tire that is a trifle too small for the wooden rim of a wagon wheel. He heats it in a ring of fire, and it goes over the fellies readily. On cooling, the iron

band fits closely, tightens up the wheel, and makes it firm. The tire is said to be "shrunk" on.

These are two examples of the multifold instances in which the expansion of bodies by heating and their contraction upon cooling are continually occurring. Liquids and gases are affected in the same manner, mercury being affected nearly six times as much as steel.

TEMPERATURE: ITS COMPARISON AND DETERMINATION

In the early years of the eighteenth century, Daniel Gabriel Fahrenheit (1686-1736), a German physicist living in Holland, was engaged in the study of heat and climate. He used alcohol inclosed in glass bulbs with a stem of fine bore, and any appreciable heating or cooling of the bulb and its contents resulted in a measurable rise or fall of the slender thread of liquid in the tube. Such an instrument is a thermometer. The difference in condition which we express by hot or cold is scientifically known as a difference in temperature. Alcohol boils before it becomes as hot as boiling water, and then, if it is exposed to the air, it gets no hotter; if it is inclosed it vaporizes, like steam, and on further heating it will burst the vessel containing it. So an alcohol thermometer will not serve to examine temperatures as high as that of boiling water. Mercury undergoes a large change of volume on heating or cooling, and remains liquid far above the temperature of boiling water. On learning these facts, Fahrenheit adopted mercury for his thermometers.

He marked the position of the mercury in the tube at the temperature of several natural conditions, such as melting ice, the human body, boiling water, etc. The winter of 1709 was unprecedentedly cold

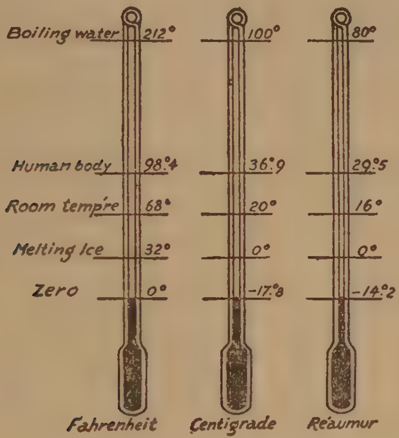
in Holland, the mercury falling to a point which was as low as Fahrenheit was able to reach by means of any refrigerating mixture he could prepare. With such a mixture of ice, water, and sal ammoniac he was able to cool his thermometer to the mark of the severest natural cold which it showed for that winter, and this temperature he chose as zero, from which to mark a scale of rising temperatures. He divided the whole space from zero to the boiling temperature of water into 212 equal parts or degrees. This scale of temperatures is the one commonly used in America and Great Britain for household purposes and to some extent in steam engineering.

The Swedish philosopher Celsius had made use of a scale of 100° for the range of temperature from melting ice to boiling water, calling the temperature of melting ice zero, and that of boiling water 100°, and when the French revolutionists revolutionized everything they adopted the Celsius scale of temperatures along with the metric system of measures, and this temperature scale, now more commonly called the "Centigrade," is the only one used to any considerable extent for scientific purposes throughout the world, except, as mentioned, in some English and American engineering practice.

For domestic purposes still another scale is in use on the continent of Europe, introduced by René Antoine de Réaumur, in which the freezing of water marks zero, and the range from that to boiling water is divided into 80°.

The temperature difference between freezing and boiling water is a fixed, definite physical quantity, although the number of degrees is different by the different scales, just as the length of a bar is fixed although expressed in other numbers when

measured in feet and inches than when measured in meters and centimeters. As 100° of the centigrade scale represent as large a range of temperature as 180° on the Fahrenheit scale, 1 centigrade degree is 1.8 times as large as one Fahrenheit degree, or 1 Fahrenheit degree is 5/9 as large as a centigrade



THERMOMETER SCALES

A comparison of Fahrenheit, Centigrade, and Réaumur thermometers.

degree. So when the weather temperature is said to be zero F., it is 32 Fahrenheit degrees below freezing, and the physicist counts it 5/9 of 32, or 17.8° below his zero—i. e., —17.8° C. When he records a temperature of 15° he means 15 centigrade degrees above his zero, which would be 9/5 of 15 Fahrenheit degrees above freezing, or 27° above 32° —i. e., 59° F.

A thermometer of mercury, however, could not be used with very high temperatures, such as would melt most metals. For such purposes, a special form

whose indications depend on electrical action is employed.

HOW A BODY IS HEATED

In the modern view the heat of a body is regarded as energy of motion of the molecules composing it, whether the motion be of translation, rotation, or vibration. Presumably it is chiefly the first. No matter by what means increased motion may be conferred upon the molecules, whether by direct mechanical effort, as friction or hammering, or by chemical action, energy of some other form is thereby transformed into this particular kind called heat. When raised to a sufficiently high temperature, the molecules of many substances will unite rapidly with oxygen. This is "combustion," and the process is a conversion of energy of chemical separation into energy of heat. The operation may be started by the friction of the head of a match, producing a high enough temperature for the oxygen of the air to unite with the phosphorus of the match, and this may be the means of igniting coal gas, or vapor of alcohol, or other combustible material.

In a flame, the kinetic energy of the minute particles, whether darting about in translation, or in rapid vibration, is very great, and as they impinge upon other molecules they increase their energy also. If the other molecules are those of a solid, as an iron bar, the flame applied directly to the end of the rod heats it, i. e., increases the energy of the molecules of iron; these, by impact, pass on their energy to adjacent molecules, and these to others, and the whole bar becomes heated "by conduction."

An increased average path of the molecules means an expansion of the body. In a liquid, any portion so heated is enlarged, becomes specifically lighter

and rises; the heated molecules communicate some of their energy to those with which they mingle; the circulation facilitates the distribution of energy throughout the body of the liquid, which thus becomes heated "by convection."

THE SCIENTIFIC MEANING OF HEAT AND TEMPERATURE

We know by experience that water, a liquid, if made cold enough becomes ice, a solid; liquid grease becomes solid tallow; on the other hand, either of these liquids, with application of sufficient heat, will boil off as a gas. But water must be colder than grease to solidify, and the latter must be much hotter than the former to boil. These substances retain their essential natures while passing through the changes of state, the only agent bringing about the change being heat. Now what does heat do to the body to change it? There is no more and no less of the material in one state than in another, and that heat is material was disproved by the work of Rumford and others, as mentioned earlier in this book.

In trying to answer our question, let us consider first the application of heat to a gas: air will do as well as any other gas. Suppose a box to be provided with a pressure gauge and a thermometer, both connected with the interior of the vessel. Also suppose the vessel to be such that its size may be kept constant. Let the temperature of the gas be that of melting ice, for which the thermometer reads 32° F. The volume is continually 1 cubic foot. On heating the gas the gauge shows an increase of pressure and the thermometer a rise of temperature. No increase of volume is effected, but the pressure is increased. What does that signify? Here is the explanation: On a preceding page we showed that the pressure

of a gas is due to the kinetic energy of its molecules. But kinetic energy is measured by half the product of the mass by the square of the velocity, and, in our box, since the mass was not altered, the effect of the heat was to increase the velocity only, and this increase of velocity caused the increase of pressure. With a rise of 1° F. in the temperature, the pressure is increased by 1/491 of what it was before heating; if the temperature is raised 2°, the pressure is increased 2/491, and so on; the increase of pressure and of kinetic energy being in just the same proportion as the rise of temperature. If the gas were cooled, the pressure would diminish in the same ratio.

After the temperature has been considerably increased, say to 100°, and the pressure correspondingly increased, with no change in the volume, suppose that the side of the box could yield to the increased pressure. In doing so it would push back the outer air, against a pressure of 2,116 pounds on the sq. ft., and this, multiplied by the distance the side was pushed, is mechanical work, brought about by means of the heat applied to the gas. *Heat, then, is energy, and temperature corresponds to energy per molecule.*

ABSOLUTE ZERO AND ABSOLUTE TEMPERATURE

We have seen that with a given mass of gas at 32° F., the volume being maintained constant, if the temperature rises or falls one degree, a corresponding increase or decrease of pressure ensues equal to 1/491 of the initial pressure. This is called "Charles's law." On the other hand, if the gas is permitted to expand with rise of temperature, then, at constant pressure, for every change of one degree F. the volume changes in the proportion of 1/491.

This is called the "law of Mariotte." The 1/491 of the pressure or volume of the gas per degree F. (or 1/273 per degree C.), at the temperature of melting ice, which is 32° on the Fahrenheit scale and 0° on the centigrade scale, means that if we started to reckon temperature from 273 centigrade degrees or 491 Fahrenheit degrees lower than that of melting ice, the variation of these quantities would be just in the same proportion as the change of temperature. Therefore this lower point, –459° F. or –273° C., is taken to represent absolute zero, and temperature, reckoned from that point, is called absolute temperature. A Fahrenheit degree is still 5/9 as great as a centigrade degree, since 1/491 is 5/9 of 1/273. On the absolute scale, in F. degrees,

–459° F.= 0° abs.
0° F.=459° abs.
32° F.=491° abs.
212° F.=671° abs.

In centigrade degrees,

–273° C.= 0° abs.
0° C.=273° abs.
100° C.=373° abs., and so on.

If the pressure, P, varies while the volume, V, is constant, the temperature, T, is proportional to the pressure.

If the volume, V, varies while the pressure is constant, the temperature is proportional to the volume.

If the volume and pressure change together (neither being kept constant), the temperature is proportional to their product; or their product is proportional to the temperature; i. e., it is some constant number, R, times the temperature.

In a formula this is written $PV=RT$.

This is one of the most important relationships in the physics of heat. The quantity R is sometimes called Regnault's constant, and sometimes simply the gas constant. How much it amounts to depends upon how we measure P, V, and T. In English units and on the Fahrenheit scale of temperature, R=53.3.

In the kinetic theory it is shown that for a given quantity of any gas, the product PV means mechanical energy; here we see that it is a definite number of times the *absolute temperature* of the gas, and the factor R expresses the amount of work expended on the gas per degree of increase of temperature. A pound of air at any temperature, with a definite pressure and the volume it will then occupy, will require 53.3 foot-pounds of work to raise its temperature one degree F., and in so doing, give it a new temperature or volume.

WHERE THESE LAWS MAY NOT BE INFLEXIBLE

If a gas, starting from the temperature of 32° F., were to shrink 1/491 part for every degree of fall in temperature, the pressure remaining constant, then when the temperature fell 491° it would shrink to nothing, something inconceivable. If, however, its volume were kept the same while the temperature fell, after a fall of 491°, the pressure would vanish. This is not inconceivable, since it simply implies a cessation of motion in the molecules. But no substances have as yet been brought to that condition, though they have very nearly reached it. We cannot be certain, however, that any theory is perfectly applicable to its extreme theoretical limits. The impossibility of a gas reducing to zero volume is evident from the fact that the molecules themselves, no matter how small they may be individually, or how

far apart in comparison with their own size, still do have some size, or fill some volume, even when they are quiescent.

The equation, therefore, cannot be accepted as rigidly applicable to the theoretical limit of temperature. The same considerations would show that Boyle's law must be modified to meet conditions in which the actual size of the molecules play a part. Mathematical formulas are exact, and give the impression that physical relations for which they stand are inflexible. But most of such generalizations require to be modified at some stage in applying them. The force between molecules may be such that when in close proximity to one another the pressure may be increased more in proportion to the space they occupy than when moving in a larger space.

All gases, if made sufficiently cold, will become liquid under great pressure, and as the point of liquefaction is approached, they depart from Boyle's law, becoming for a while more compressible, until a limit is reached, after which the reverse occurs. Hydrogen is an exception. It steadily becomes less compressible as its volume is reduced.

CHAPTER XVII

EFFECT UPON A BODY OF APPLYING HEAT TO IT

THE application of heat produces results of the same kind with a solid or a liquid as with a gas, except at certain stages of the process, in which the body is changing its state. In general, the effects are:

I. Rise of temperature.
II. Expansion.
III. Change of state.

I. A rise of temperature in a body means an increase in the *average* kinetic energy of the molecules. This increased energy may be conferred upon the molecules in various ways: by contact with more energetic molecules in another body, as in a flame; or by the effort to transmit an electric current; or by direct mechanical work of hammering, friction, stirring, etc.

The temperature of a body, represented by the average kinetic energy of translation of its molecules, should not be confused with the heat of the body, which is the *aggregate* energy of all its molecules. A vessel of water may have been brought to a high temperature, and it will feel hot to the hand, though this is a very uncertain test of temperature; but a cupful of the water will be just as hot—i. e., have the same temperature as the whole mass of water, for the average energy of its molecules is the

same. But the heat of the large mass exceeds that of the cupful in proportion to the mass of liquid in it.

Generally, where no change of state is produced, with a definite mass of a substance, the quantity of heat applied will vary with the change of temperature produced, and so will the expansion; and the temperature of a thermometer changes in proportion to the heat applied to it, and is shown by the expansion of the material in it.

II. With few exceptions, bodies expand with a rise in temperature, the fractional part by which they increase in one direction, e. g., length, for one degree, being called the coefficient of linear expansion. This is in all cases a very small fraction. As only solids have a fixed shape, it is only to them that linear expansion applies. For a thin sheet the fractional increase of area per degree is the coefficient of superficial expansion, and is twice as great as the linear coefficient for the same substance. Liquids and gases are rated by their increase in volume, for which the coefficient is three times as great as for linear expansion.

The expansion of steel compared to that of brass is as 12:19; consequently a piece of brass 12 inches in length will elongate as much with a given change of temperature as one of steel 19 inches long. This difference in rates of expansion is utilized in the arts in many ways. If a strip of brass is securely riveted to one of iron of equal length, at a given temperature, say 70° F., then on heating this compound bar the brass expands more than the iron and becomes the longer strip. The bar will take on a curved form with the brass on the outside; if the bar is cooled below the initial temperature, the brass contracts more than the iron and the bar is curved

the other way, the brass now being on the inner or shorter side of the curve.

If such a composite strip of two metals be wound spirally in a coil about an axis, and one end be fixed to a stud as at S, any change of temperature will

ACTION OF THE METALLIC THERMOMETER

increase or decrease the curvature of the successive spires, and will wind up or unwind the coil. The end E then turns around the axis AP. It may be attached to one end of a lever pivoted at P, with the other end carrying a toothed rack R. This engages in a small pinion W, which bears on its

shaft a long pointer I. With any movement of E the index I moves over a dial marked suitably in degrees, and thus shows the temperature like the column of mercury or alcohol in a liquid thermometer. This is a convenient form of thermometer, very common now in cars and other public places. The dial is the face of a cylindrical case containing such mechanism.

Constancy of a pendulum clock requires that the pendulum shall swing always in exactly the same period of time, and this period depends upon the

DIAL OF THE METALLIC THERMOMETER

length of the pendulum. If the pendulum itself is a rod with a massive ball or disk at the end, the "length" is virtually the distance from the axis of suspension to a point in the ball, near its center, known as the center of oscillation. If the pendulum is of metal, this length varies with changing temperature and the clock is not regular. On that account a wooden rod is preferable to one of metal, but this, too, is open to some objection. A form known as the "gridiron" pendulum makes use of two metals with different coefficients of expansion so combined as to maintain a constant length of the oscillating body.

The balance wheel of a chronometer, or high-grade watch, is compensated for changes of temperature by a similar combination of metals having different coefficients of expansion.

A thermostat is a contrivance to keep the temperature of a room or vessel within prescribed limits.

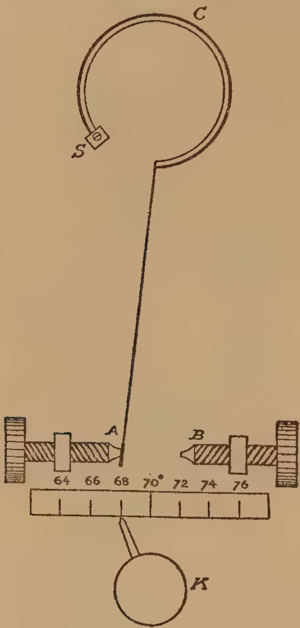


DIAGRAM OF HOUSEHOLD THERMOSTAT

The unequal expansion of metals is utilized to actuate an electromagnet, which controls the furnace draughts through clockwork.

It finds a place among minor applications of physics to thrift, health, and comfort. The householder, desirous of avoiding excessive heat or cold in winter, seeks some self-regulating arrangement for his furnace that shall act in his absence, or while he sleeps.

This is supplied by a common form of thermostat which makes use of unequal expansion in metals to actuate an electromagnet which controls a clockwork connected with the furnace draughts.

PECULIAR EXPANSION AND CONTRACTION OF WATER

Most substances change continuously in the same way, as long as they are in the same state—solid, liquid, or gaseous. Water is a notable exception. With a given mass, starting at a temperature of 212° F. (or 100° C.), water steadily contracts with cooling until the temperature is 39.2° F. (or 4° C.). It is then at its smallest volume and consequently its greatest density. This is the condition in which it is taken as a standard of density. It then contains 1 gram per cubic centimeter, or 62.4 pounds per cubic foot, and its specific density is 1. At 100° C. the volume of 1 gram is 1.043 cubic centimeter, or the density is 0.96 gram per cubic centimeter.

But on cooling below 39.2° F., or 4° C., the volume, instead of continuing to decrease, increases until it reaches the freezing point 0° C., or 32° F., when the volume has become 1.000129 cubic centimeters, and its density 0.999.

Just here occurs another peculiarity which water shares with a very few other substances. On still further cooling, it freezes, or changes from liquid to solid, and in so changing it increases in volume to 1.092 times as much, or about one-eleventh. The density of ice is, therefore, 0.916, and being thus specifically lighter than water, it floats with about one-tenth of its volume above the water. In sea water of specific density 1.03, about one-ninth of the volume of an iceberg would be exposed, 0.89 being submerged.

The consequences of this anomalous behavior of water are very interesting. Suppose a lake exposed to a clear wintry sky gets cool at the surface; the superficial layer sinks and cools the water beneath it, and so, gradually, the whole body is chilled until the temperature of 39° F. is reached throughout, and the water is everywhere at its maximum density.

If the process continued in the same manner, the lowermost stratum would freeze as soon as the upper, and the lake would be solid ice to the bottom. Even without this, if the surface water in freezing still contracted instead of expanding, it would sink to the bottom, and again in a short time the entire body of water would be solidly frozen. Death to all creatures within it would be the result.

But just when the situation thus becomes critical, any further fall in temperature on the surface layer is accompanied by expansion, and so that layer becomes lighter and remains at the top, and when it freezes it becomes still lighter and turns into a firm protecting roof on the water beneath.

Water, however, is not quite alone in expanding on solidifying. Molten bismuth and antimony do likewise, and so does iron. It is this peculiarity that makes iron available for castings, for when the liquid iron in the mold solidifies, it fills out the space completely. If the liquid contracted on solidifying, the mold would not be filled. Gold and silver contract on solidifying, so that coins of those metals cannot be cast, but must be pressed or stamped to give them the desired form and marking.

If water, or molten metal which expands by solidifying, is confined, it will burst a strong vessel when it becomes solid. The freezing of water in holes or channels was employed in early times to break blocks

of stone into a desired size or shape. To-day we are made aware of this effect by the bursting of water pipes that have not been sufficiently protected from cold weather.

By annoying and sometimes costly experience the motorist learns to appreciate the effect of heat upon the pressure of the air with which his pneumatic tire is inflated. Starting out with a pressure of eighty pounds in the tire, at a temperature of, say, 70° F., or 529° absolute, a rise of one degree would cause an increase of 1/529 in volume, if there was no increase of pressure. Driving upon a hot roadway, the tire and its inclosed air may soon be raised to 120° F., or fifty degrees higher than at first. Some increase in size occurs, but very little; while the increase in pressure for fifty degrees' rise in temperature is nearly one-tenth, or about eight pounds per square inch. The worn tire, not able to withstand much over the eighty pounds with which it started, explodes under the ninety pounds to which it is raised.

III. Change of state.

Although all substances are capable of existing in a solid, a liquid, and a gaseous form, there are only a few that we are accustomed to see in more than two of these states. We may trace a substance through the three in succession by beginning at either end of the series. With those that we know more familiarly as solid it may be simpler to start from the solid state; others which we know more commonly as gases, we may follow better by beginning with them in that state. Water, a standard for so many purposes in physics, is almost as familiar to us in one as in the others of the three states. We do not usually think of ice as something that can be

warmed up, but if a block of ice is at a temperature of zero F., it is much colder than freezing, and can undoubtedly be warmed by 32° before it will melt. When brought to this temperature, however, ice will not get any warmer with continued application of heat, but will melt into water, at the same temperature, and if the solid ice is kept in contact with the melted ice while heat is still applied, it will all melt, and the resulting liquid will still have the temperature of 32° F.

Now, to explain this, we must remember that in the solid form of a body the molecules are supposed to oscillate around mean positions. Each is confined to a very small space which it never leaves. As the temperature rises the molecular agitation increases, and at length becomes so violent that the molecules break away from their imprisonment and wander about indiscriminately among one another. In this state the substance is said to be in the liquid form. But work was done in overcoming the forces which held the molecules confined in the solid state, and this conferred upon the molecules an increase of energy, even without rise of temperature. It is really the work of liquefaction. It used to be called "latent heat of fusion," but it is not latent but effective, and without it the liquid would revert to the solid form. The term latent heat, however, is still retained, and used to some extent. Further heating again raises the temperature, increasing the energy of the molecules, until they finally break the bonds of the liquid state and assume the gaseous form, in which the energy shows as pressure and temperature. On reaching the point of changing from a liquid to a gas, the liquid does not get hotter with the addition of heat, but is simply converted into a gas at the

same temperature, and much energy is thus expended which used to be regarded as heat latent in the gas. But, as in the other case, it is not latent; it is effective in maintaining the greater energy of the molecules, and if it were withdrawn the gas would revert to the liquid state.

We are all accustomed to see metals (except mercury) in their solid form, some of them occasionally in a liquid or molten state, but few of them in the gaseous condition. Mercury becomes solid or freezes at the temperature of 36.4° below zero F., and therefore cannot be used for thermometers in regions where temperatures go below that figure. Air, and most substances which we know commonly as gases, we do not often see in any other state, except steam, which is even more common in its liquefied character of water; but the other gases have been liquefied, and solidified, too. There is, then, a temperature for every substance at which it will change from the solid to the liquid state upon the further application of heat. This temperature is called the melting point of the substance, and is almost but not quite independent of the pressure upon it at the time of liquefaction.

Likewise, there is a temperature for every substance at which it will be converted from the liquid to the gaseous state by further application of heat to it, but this temperature is so dependent upon the pressure on the liquid that it is definite only for a definite pressure.

As long as a body is not near a change of state the rise of temperature appears to progress steadily with steady application of heat. If a pound of water at 80° be mixed with a pound at 40°, the mixture of two pounds will have a temperature of 60°, the one

pound having risen just as much as the other fell, as if the heat lost by one was acquired by the other, thus producing an equal change of temperature in each. Without heat being anything tangible, therefore, we may measure it by the change of temperature it will produce in a body. It would require twice as much heat to raise two pounds of water one degree as to raise one pound one degree, and ten times as much to raise a pound ten degrees as to raise it one degree. So a unit for measuring the quantity of heat is chosen as "the heat required to raise the temperature of one pound of water one degree Fahrenheit." This is known as the *British thermal unit* (B. t. u.). In c. g. s. units the unit of heat is the heat required to raise the temperature of one gram of water one degree centigrade. It is called a calorie. The former is used in engineering practice. The latter is the unit in almost exclusive use for scientific investigation. One B. t. u. equals 252 calories.

When the heat of a body was attributed to the amount of "caloric" it contained, every body was supposed to have a definite capacity for heat. That view is no longer held, although the phrase "capacity for heat" is retained. By heat capacity is now meant, not the quantity of heat the body can possibly take in or give out, but the quantity that will produce in it a definite change of temperature. The capacity, like the quantity of heat itself, is determined by some effect which heat produces upon the body, and the particular effect that has seemed most appropriate for this purpose is change of temperature. With either the B. t. u. or the calorie as a measure, it is found that the amount of heat that will make a given change of temperature is different

for different bodies; more for two pounds of a substance than for one pound; either less or more for a piece of lead than for a piece of tin, depending on how great a mass of either metal is in the lump. But, in any case, the number of units of heat required to raise a body one degree in temperature is the capacity of *that body* for heat.

When bodies of various substances, all of equal mass, are compared, it is found that their capacities for heat are very different, that of mercury being only one-thirtieth as large as that of water.

Here, again, water is taken as a standard or basis of comparison, and the heat capacity of any other substance in comparison with that of water, pound for pound, or gram for gram, is called the *specific heat* of that substance. The specific heat of water itself, then, is unity; and since water has an exceedingly high capacity for heat, the specific heat of other substances is a fraction, or less than unity. As examples, for copper, it is .094; for ice, it is 0.5; for steam, 0.421, for mercury, .033, etc.

Gases expand so much with a slight rise of temperature, that when heat is applied to them, much of the energy is at once transformed into the work of pushing out the enveloping surface against the constant external pressure of air or water or whatever the medium in which the vessel may be immersed. If the gas did not thus expand, less heat would be needed to raise its temperature; the specific heat, then, of a gas under constant pressure is sensibly higher than with constant volume. The ratio of the two specific heats enters into certain phenomena in other branches of science. This is notably the case in connection with the velocity of sound in a gas. It affords a beautiful illustration of the interrelation-

ship connecting the various divisions of physics. The ratio for air is 1.4; and varies with other gases from 1.34 for steam at 212° F. to 1.63 for helium.

ELASTICITY

Elasticity is especially important in connection with engineering work; in physics it is more particularly concerned in phenomena of vibration and of wave motion, and as these are at the base of light and sound, as well as certain movements of liquids, the property of elasticity is fundamental in them. It causes the return of a body to its normal condition after the body has been distorted; and because of the inertia of matter, when a distorted body springs back to its initial condition or position, it is carried beyond that extreme from which it again returns, only to repeat its performance, until its energy is expended in producing molecular effects and in overcoming external resistances. Motion such as this is vibration.

The distortion of the body may occur in two ways, and the consequent reaction of the body is exerted in two corresponding ways by the molecular forces in the body, viz.: (*a*), the body may be extended—opening the intermolecular spaces; or it may be compressed into smaller bulk. The force that is applied is reckoned per unit area of the section on which it acts, as pounds per square inch, for example, and this is called the *stress* to which the body is subjected; if it is merely to change the length as in stretching a wire, the fractional part which the change in length is of the unstretched length—one-millionth, or one-thousandth, or one-tenth—this fraction is called the *strain*, and the measure of the elasticity is the ratio of the former of these two

quantities to the latter; or the stress divided by the strain. It is called the "coefficient" or the "modulus" of elasticity, every kind of substance having a modulus peculiar to itself. If the strain is too great, the body will not return completely to its former condition when the stress is removed, but will remain somewhat distorted. The extent to which it may possibly be strained and yet recover itself is its elastic limit, and the general law of elasticity is that, *within the limits of elasticity the stress is proportional to the strain.*

If only the longitudinal distortion of a body is considered, as in the elongation of a wire, the modulus is known as "Young's modulus."

(*b*) A body might, however, be so pushed or pulled as to make one layer slide over its adjacent layer, like the leaves of a book in opening or closing it. If the leaves were linked together by rubber bands between them, the sliding would be resisted, and the book would regain its form on removal of the applied force. This is the kind of effect that is felt between the successive cross-section layers of a rod if one end is fixed and the other end is twisted; some such sliding occurs with every section of the rod and it may amount, in all, to a complete turn or many turns. This sliding elasticity is called *shear*—plane shear in the first described form, torsional in the second. In the ordinary bending or flexure of a bar the fibers on the convex side are elongated and those on the concave shortened, and the elasticity is measured by Young's modulus. This cannot be applied in measuring the elasticity of fluids, and as they offer no resistance to change of shape, they have no shearing elasticity. For them elasticity is the reaction against a change of volume, and its modulus

is called the "bulk modulus." The stress again is the force per unit area, but the strain is the proportional part by which the volume is altered.

In solids and liquids, a great force is necessary to produce a small change in size, and any effect, such as heating or cooling, makes no appreciable difference in the elasticity of the body, but with gases this is not so. When a gas is altered in volume or pressure without any change in temperature, heat being allowed to leave the body or to enter it so as to keep the temperature constant, it is said to change *isothermally* (which means of the same temperature). It is only in an isothermal change that Boyle's law applies.

To determine the elasticity of a gas under such conditions, suppose we had a cubic foot, say, of gas at standard atmospheric pressure, 2,116 pounds per square foot. If the pressure were increased by one-tenth, i. e., so as to become 2,327.6 pounds per square foot, the volume would be reduced by one-tenth, or to nine-tenths of a cubic foot. The force producing this compression is 211.6 pounds per square foot, which is called the *stress*, and the change of volume produced by it is one-tenth, which is called the *strain*. The elasticity is stress divided by strain, which works out, 2,116 pounds per square foot—just the same as the pressure, at first. If any other figures are applied, either for compression, or for an increased volume, under Boyle's law, the elasticity will be found always to be the same as the initial pressure.

If no heat is allowed access to the gas when it is cooled, or escape from it when it is heated, a change of volume or pressure under such conditions is called *adiabatic* (which means, that cannot be passed

through, as if the gas were inclosed by walls through which heat could not pass, either in or out).

When a gas at atmospheric pressure, as in the above instance, is heated adiabatically until its volume is increased one-tenth, and then a pressure of 211.6 lbs. per square foot, or one-tenth the original pressure is applied to the gas, this will not reduce it to the original volume; the reduction is less than one-tenth; consequently the elasticity, the stress divided by strain, is 211.6 divided by less than one-tenth. This quotient is greater than 2,116, the original pressure. Both by theory and by experiment it is found that the adiabatic elasticity of a gas exceeds the isothermal, in exactly the same ratio that the specific heat at constant pressure exceeds that at constant volume. This ratio for air is 1.4.

CHAPTER XVIII

FREEZING, A WARMING PROCESS

WHEN a body melts it takes in heat and when it solidifies it gives out heat. When the temperature has been raised to the melting point, the addition of more heat does not make the body any hotter, but changes it into a liquid. If the increasing liquid and the decreasing solid are kept intimately mixed, the temperature remains a constant until the solid is completely melted. Thereafter, with the addition of heat the temperature again rises. In the process of melting, however, a measurable quantity of heat is taken in by the substance and seemingly disappears. This, as we have mentioned before, is called the latent heat of fusion, and is measured by the number of heat units required to melt a unit mass of the substance. This process may be reversed. Starting with a substance in the liquid state, on cooling it, when it reaches the temperature at which it passes indifferently from liquid to solid, or the reverse, with any further effort to lower its temperature, it will solidify, and in so doing will give out as much heat as was absorbed in melting an equal quantity of the solid.

Mix a pound of ice at 32° F. with a pound of water at 212° F., and when the ice is completely melted there will be two pounds of water having a temperature of 51° F. The ice was first changed into ice water, for which an unknown quantity of heat was

required, and then the pound of ice water was raised from 32° to 51° in temperature, which required 19 B. t. u.'s. The heat was given out by the pound of hot water in falling from 212° to 51° in temperature, emitting 161 B. t. u.'s. So the heat required to melt the ice was the difference between 161 and 19, or 142 B. t. u.'s, which is the latent heat of water, or more properly, that of melting ice.

In c. g. s. units latent heat of fusion is the number of calories required to melt one gram of the substance. For ice (solid water), it is 80 calories.

By pouring a known mass of molten metal into a known quantity of water, the metal is solidified and the temperature of the water is raised. This means that the solidifying of a substance is accompanied by liberation of heat. In the case of water, for every pound of ice that is produced, as much heat is given out as would raise 142 pounds of water one degree in temperature. Thus we see that freezing is decidedly a warming process! Now, since the specific heat of air is .242, or just about one-quarter that of water, the same heat would raise 568 pounds of air one degree. But 568 pounds of air at ordinary pressure would fill a room 20 x 25 feet square and 14 feet high. This shows the reason for the precaution sometimes taken to protect vegetables from freezing, in cellars or bins, by placing in their neighborhood tubs of water when a very cold night threatens. The vegetables would endure a temperature considerably below 32° without serious injury, and before the air becomes as cold as that, the water freezes, with a consequent check upon the fall of temperature.

The melting points given in the table are for a pressure of one atmosphere upon the substance, and with most of them this varies but little, although in

some cases, with extreme change of pressure, the change in melting point is appreciable.

TABLE OF MELTING POINT AND LATENT HEAT OF FUSION

	Melting Point		Latent Heat of Fusion	
	Fahrenheit	Centigrade	B. T. U.'s to melt one pound	Calories to melt one gram
Aluminium	1215°	657°	137	77
Beeswax	126°	62°	75	42
Carbon	7200°	4000°	...	...
Copper	.....	1083°	...	43
Glycerine	.....	13°	...	42
Gold	.....	1062°	...	...
Hydrogen	—434°	—259°	...	...
Iron	.....	1500°	...	35±
Lead	.....	327°	...	5.6
Ice	32°	0°	142	80
Mercury	.....	—38.8°	5.4	3
Nickel	.....	1435°	...	4.64
Nitrogen	—329°	—210.5°	...	...
Phosphorus	79°	44°	9	5
Oxygen	—391°	—235°	...	...
Platinum	.....	1750°	...	...
Paraffin	.....	52°	...	35±
Silver	.....	961°	...	21
Sulphur	.....	115°	...	9
Tin	.....	232°	...	14
Zinc	.....	418°	...	28

Also, the very high capacity of water for heat makes it especially suitable for heating a house. It is this, too, that gives its merits to a hot-water bottle. It is not that the water retains its heat so long—the heat it retains is not doing any good, the benefit comes from the heat the water does not retain—but the advantage lies in the fact that it can give out a great deal of heat and still be not much cooler.

Many alloys have a lower melting point than either of the metals composing them. They are used for soldering. An alloy of equal weight of lead and tin melts at 188°C.; with 3 parts of lead and 5 parts of tin, at 176° C.; and with 2 of lead and 5 of tin, at

170° C.; with 1 of lead, 1 of tin, and 4 of bismuth (Rose's fusible metal), at 94° C., or below the temperature of boiling water.

A few substances which take a crystalline form on solidifying have a larger volume in the solid than in the liquid state. This is notably so in the case of water. These substances, when solid, float in their liquids, and if they are liquefied by raising their temperature their volume shrinks. Now, pressure applied to them, when solid, tends to decrease their volume, thus producing an effect similar to that of heat, i. e., it causes them to melt. As a consequence, such substances when under pressure must be colder than their freezing point, in order to remain solid. Ice, for example, must be colder than 32° F. to remain ice, and if not colder it will melt simply by the application of pressure, without additional heat. This lowering of the melting temperature of ice is only about nine degrees for an increase of six hundred atmospheres, or one and one-half hundredths (.015) of a degree for an increase of one atmosphere; and for other solids, such as iron and bismuth, it is even less. Still there are circumstances under which the pressure becomes enormous and the lowering of the freezing point is considerable. With bodies that expand on melting, as is the case with most substances, the application of pressure makes it more difficult for them to melt, and they must be made hotter than would otherwise be necessary—their melting point is raised by pressure. With such a substance, the greater the pressure the higher its melting point. Benzene, having been frozen in a vacuum at 41.5° F., under 3,387 atmospheres pressure, must be heated to 178.5° F. to melt it; but under one atmosphere pressure it boils at 177.8° F.,

so that its freezing point under one pressure is higher than its boiling point under another!

The effect on ice under reversed conditions has been observed. By keeping it in a vacuum, the pressure being almost nothing, it may be heated far above 32° F. before it will melt.

POSSIBLE CONDITION IN THE INTERIOR OF THE EARTH

These facts lead to some interesting deductions, especially regarding the interior of the earth. The mean density of the earth is 5.527, i. e., the earth is composed of materials which, on the average, are about 5.5 times as heavy as water. It is likely, therefore, that within the globe the material is of a nature similar to that of metals and ores generally, which expand on melting, and which, under great pressure, remain solid, even at a very high temperature. It is thought that the great heat within the earth would necessarily make its interior a molten mass; but, if the earth were liquid throughout and of uniform density equal to its mean density, the pressure within a few hundred miles of the surface would increase at the rate of somewhere about 800 atmospheres (or nearly 5½ tons per square inch) per mile of depth. So we can understand why the materials forming the interior of the earth may be solid though at a temperature far above their ordinary melting points. Indeed, the physical relations would permit the assumption of a solid shell or crust of earth surrounding a molten layer, which, in turn, envelopes a solid globe within it.

A block of ice about three inches square in cross section is encircled by a loop of fine wire from which is suspended a weight. The wire passes through the

ice, but is always solidly incased in it: the ice is not cut apart. Under the wire the pressure is great, and the ice melts; the conversion of solid into liquid, however, is attended by the absorption of heat (the heat of liquefaction, no matter whether the liquefaction be in consequence of heat or pressure), and as this can come only from the ice around the wire and the wire itself, the temperature of the wire, the adjacent ice, and of the water immediately beneath the wire is below 32° F. The wire sinks, the water flows around and above it, the pressure upon it is released, and it is cold enough to refreeze, the ice being solid above the wire as the latter moves down through the block.

If the wire is a fine steel piano wire one-fiftieth of an inch in diameter, it will easily carry a weight of twenty pounds. If the length of it that is pressing the ice is three inches, the area under pressure is three-fiftieth square inch, which, with a weight of twenty pounds, makes a pressure of 333 pounds per square inch or about 23 atmospheres; this would lower the melting temperature not quite half a degree—not much, but enough to make all the difference between melting and freezing.

The great masses of ice constituting glaciers have a "flow," or movement down the mountain slopes, and numerous explanations of this movement of a "solid river" have been offered. Possibly a complete explanation needs more than one kind of physical action, but there is good reason to believe that the phenomenon is largely an instance of regelation. Under the pressure of the immense depth of snow and ice, the lower layer melts and oozes down the surface of the rocks beneath wherever there is escape for it. Released from pressure at places, it

refreezes, but slowly the great body continually sinks by the melting beneath.

The glistening surface that shows the track of a cart wheel which has crunched over a hard, snow-covered roadway, consists of ice, resulting from the refreezing of the snow which was momentarily melted under the great pressure concentrated on a small space by the passing wheel.

Boys know that dry, cold snow will not stick together in a snowball, but if the snow is nearly warm enough to melt, then, when pressed together, it becomes firm and hard. This is not simply that it has become more compact snow, but bits have been melted and refrozen, and the ball has become harder in consequence of this regelation.

CHAPTER XIX

BOILING TEMPERATURE AND BOILING POINT

THE energy of motion of molecules varies with the temperature, and if the pressure above a liquid is sufficiently reduced, the energy may be great enough at any temperature to break the bonds that hold the molecules in a liquid state. This is occurring, in slight measure, all the time at the surface of a liquid, where molecules having more than the average energy continually escape as gaseous molecules. But when the pressure is so reduced that the change into a gas occurs in the interior of the liquid, the bubbles of gas rise through the liquid, and burst at the surface, and the liquid is said to be "boiling." If this is effected by applying heat at the base of the liquid, small bubbles are formed in the lower portion, and rising into the colder liquid they collapse. With further heating this becomes rapid enough to cause the singing that is heard just before boiling begins.

When a space has so much vapor in it that an increase of pressure upon it condenses it into liquid, the vapor is said to be "saturated," and the pressure it then exerts is the greatest pressure it can exert at that temperature. Now, the pressure of a gas that is just sufficient to enable it to escape from its liquid into the atmosphere is equal to the pressure of the atmosphere upon the liquid. Also, the

saturated vapor of every kind of liquid exerts its own amount of pressure upon the liquid beneath it, this pressure varying with the temperature.

Saturated water vapor, when heated to 212° F., exerts a pressure equal to 30 inches of mercury in the barometer, and if the atmosphere is at that pressure, water, open to the air, will boil at 212°. Saturated vapor of alcohol exerts a pressure of 30 inches of mercury at 173° F., so alcohol boils at 173°. By the "boiling point" is to be understood the temperature at which the pressure of the vapor equals a standard atmosphere, or 30 inches of barometer column. The liquid then boils under that pressure at that temperature. But, inasmuch as a liquid will boil at any temperature if the pressure is low enough, the temperature of boiling is not necessarily the same as the boiling point in the common meaning of that term. Under low pressure it may boil at much lower temperature than its technical boiling point; and if the pressure is high, it may be heated far above its boiling point without boiling.

Because of the difference of temperature at which different substances will boil under the same pressure, a mixture of different liquids which do not unite chemically can be separated by successive distillations. When the mixed liquid is brought to the boiling temperature of the most volatile constituent, this will boil off, in its own vapor, which may be condensed as it escapes. Afterward the remaining mixture is raised to the necessary temperature for boiling off another ingredient, and so on. This process is known as "fractional distillation."

It sounds like nonsense to talk of making water boil by cooling it, but that is just what the so-called "Culinary Paradox" accomplishes. Water is boiled

in a flask until the air is all expelled and the flask contains only hot water and steam. The source of heat is then removed, the flask is securely stoppered and inverted, and ebullition subsides as the liquid cools. But the application of cold water to the part of the flask inclosing the vapor condenses the latter, lowers its pressure, and thereupon the water again boils violently. This renewal of ebullition is evidently a consequence of the diminution of pressure by condensation of the vapor above the liquid. If such reduction of pressure is brought about by any other means than by cooling the vapor, the resumption of boiling will be accomplished just as well. So, if water at a temperature below 212° F. is placed under the receiver of an air pump, and the pump is set in action, the pressure upon the liquid is reduced, and when it is as low as the saturation pressure of the vapor for the temperature the liquid then has, it will boil. The pressure of saturated water vapor at freezing temperature is 4.6 millimeters, or 0.18 inch of mercury column, and if the pressure in the receiver of the air pump is lower than this (which is not an exceptionally high vacuum) the water will boil although its temperature is at the freezing point. In that case, it becomes equally cold throughout, and ice at once begins to form, and if the pressure is kept low, the entire body of water will solidify, and we witness another paradox — water freezing while it is boiling!

When a liquid is brought to boiling at a lower temperature than would be needed if the pressure were greater, it cannot be made hotter unless the pressure upon it can be increased.

The lowering of the boiling temperature by reducing the pressure is made use of in the arts in

various ways, especially in the manufacture of sugar. In the vacuum pans, in which cane juice or sirup is evaporated to concentrate it, too high a temperature will carbonize and darken the product. This is avoided by boiling the liquid and evaporating the water from it in a partial vacuum, where the boiling temperature is lower. At high elevations, such as mountain tops, the atmospheric pressure is low, and in the open air water cannot me made hot enough to boil an egg. The white of an egg will begin to harden under prolonged heating at about 160° F., or higher if it contains some mineral salts, which it usually does. To harden with a few minutes of cooking, it will require an appreciably higher temperature—200° F., or more. At the Gorner Grat, above Zermatt, Switzerland, a favorite spot with tourists, at an elevation of 10,300 feet the barometer reads 20 inches and the boiling temperature of water is 192° F.—twenty degrees below the boiling point. In the city of Denver, Colorado, at an elevation of one mile above sea level, where the pressure is twenty-four to twenty-five inches, the temperature of boiling water is only about 200° F.

When water is inclosed in a tight boiler the vapor rises in pressure upon the continued application of heat, and then the liquid also becomes hotter. If the steam pressure in a boiler is brought up to a gauge reading of 100 lbs., that means an actual gas pressure of 114.7 lbs. per square inch, or nearly eight atmospheres, and the temperature is 338° F. As long ago as 1681 a form of vessel was devised by Denis Papin in which materials requiring a high temperature to soften or cook them could be placed and steamed. This was known as "Papin's Digester," and is of further interest in the arts as

the earliest use of the *safety valve*, also Papin's invention. For a long time this method of superheating has been employed for reducing gristle and other refractory animal tissue in the manufacture of glue or other products, but recently it has been brought within the reach of ordinary domestic practice in the form of a "pressure cooker," which accomplishes the cooking at a higher temperature, in less time and with smaller consumption of fuel, than in open vessels.

Hydrogen, coal gas, air as a mixture, and its constituents, oxygen, nitrogen, etc., and many other familiar substances, are always gases at such temperatures and pressures as we are accustomed to, and until comparatively recent times they had never been reduced to the liquid forms. Their boiling points therefore must be very low. Many will not liquefy under any amount of pressure, unless at the same time their temperature is reduced far below that of freezing water, and even then only under a pressure of many atmospheres. This temperature below which a gas may be liquefied by pressure, but above which no amount of pressure will cause it to become liquid, is called the "critical temperature," and the pressure necessary to liquefy it at that temperature is sometimes called the "critical pressure."

For water the critical temperature is 689° F. (365° C.), and the pressure 194.6 atmospheres, or nearly 3,000 pounds per square inch. Above that temperature no amount of pressure would make of steam anything but a gas. If water were put into a strong vessel, nearly filling it, and heated, steam would be formed over the water at 212° F., and the pressure gauge would read zero (meaning nothing above the air pressure). As the thermometer

showed a higher temperature the gauge would show a higher pressure. When the temperature reached 688°, more of the water would have been converted into steam, but not nearly all, and the pressure would be about 190 atmospheres, or 2,800 pounds per square inch. When the temperature became 690° there would be *no water* in the vessel; it would all have changed into steam at once, with no visible manifestation at all. At one instant it would be water and visible, at the next, all vapor and invisible. It is difficult to perform the experiment with water, but is comparatively easy with gases like carbon dioxide (carbonic acid gas), or nitrous oxide (laughing gas), whose critical temperature and pressure are not remarkably high, although they were formerly considered permanent gases. Samples of these gases in strong glass tubes are familiar pieces in the equipment of physical and chemical laboratories and lecture outfits, and they can be readily carried through the above-described changes.

For air the critical temperature is –220° F., and pressure, 39 atmospheres. Thus –220° F. is for air what + 689° F. is for water. Above 689° water is infallibly a gas, and above –220° air is assuredly such. At lower temperatures the gas will be liquefied at less pressure than is required at the critical temperature. At 212° water needs only one atmosphere of pressure, so that 212° is the boiling point of water. But air to be liquid under the pressure of one atmosphere must be cooled down to –312.6°. To be liquid at all, it must be as cold as –220°, although if its temperature can be reduced below –312.6° F. it will liquefy with even less than one atmosphere pressure.

Following are the critical values of temperature and pressure and also the boiling points for various

substances, with a small margin of error in some cases where observers have differed. It will be seen that, in hydrogen and helium, temperatures very near the absolute zero have been attained.

TABLE OF CRITICAL TEMPERATURES, PRESSURES, BOILING POINTS, ETC.

	Critical Temperature.		Crit. Pressure Atmospheres.	Temp're of saturated vapor at 30 in. barometer pressure			
				Boiling Point.		Freezing Temperature	
	F.	C.		F.	C.	F.	C.
Water	689°	365°	194.6°	212.°	100.°	32.°	0°
Air	-220	-141	38	-312.	-191		
Ammonia	268	131	113	-28.	-33.5	-102	-75
Carbon Dioxide	88	31	77	-108.8	-78.2	-69	-56
Helium	-450.	-268		-451.8	-268.8	-457	-272.
Hydrogen	-401.7	-234.5	14c	-421.6	-252	-436.	-260
Nitrogen	-229.	-145	34	-317.	-194	-346.	-210
Oxygen	-180.	-118	50	-294.7	-181.5	-376.6	-227

THE LATENT HEAT OF VAPORIZATION

No matter how vaporization of a liquid is brought about, whether by raising the temperature or by lowering the pressure, after the molecules escape in vapor the average kinetic energy of those remaining in the liquid is not so great as when the others were still with them, and consequently the temperature falls—rapidly if the vaporization is rapid and no heat is supplied. Just as freezing is accompanied by the liberation of heat, boiling is due to an absorption of heat, a cooling process. As the liquid boils away it passes into vapor (steam if the liquid is water) which has the same temperature as the liquid, just as a solid melts into a liquid of the same temperature. In this process of vaporization, as in that of liquefaction, a continuous supply of heat from somewhere is necessary, and the quantity of heat required to convert a unit mass of liquid into gas, with no rise

of temperature, is called the "latent heat of vaporization." For any given substance, the higher the temperature at which this occurs, the less additional heat is required for its conversion. The term is usually applied, however, to change from liquid to gas by boiling under a pressure of one atmosphere and at the corresponding boiling temperature. Like the latent heat of fusion, it is expressed in B. t. u.'s per pound, or calories per gram. For water at 212° F., it is 966 B. t. u.'s per pound, or 537 calories per gram.

Liquids that vaporize at moderate temperatures under atmospheric pressure are called "volatile," and if in vaporizing they absorb a large quantity of heat, they are utilized for producing low temperatures, or refrigerating. Alcohol, carbon disulphide, ether, and ammonia—especially the last two—are useful in that way. The skin of a patient in fever may have a temperature of 100° F. or higher, but if bathed with alcohol, the liquid evaporates rapidly, with a large absorption of heat, and a consequent reduction of the surface temperature. The effect of ether is still more marked; applied to mucous surfaces, as the gums of teeth to be extracted, the tissue and nerves are benumbed by the cold and temporary anæsthesia is produced. Heat will be absorbed in evaporating at any temperature. It is an old practice to place water in a porous jar, an unglazed earthen pot, and expose it to a current of air; the water oozing through the jar evaporates rapidly, the heat of vaporization coming from the jar as well as from the air, and the temperature of the vessel and its contents is lowered.

Sometimes the mixing of two substances is attended by the evolution of heat. In the reaction that

occurs when one substance is dissolved by another, the molecular attractions may confer upon one set of molecules greater energy than was expended in breaking up their connection with others of their own kind, and then the temperature rises. More frequently, when a crystalline substance is dissolved in a liquid, heat is absorbed from both substances in reducing the solid to a liquid, and the temperature falls. A solution of sal ammoniac in water in equal parts will reduce the temperature to 27° F. below the freezing point of water. An intimate mixture of two solids may be attended by a similar result. These combinations are called "freezing mixtures." The most common is that of ice and salt. If the ice is shaved or ground fine, or is in the form of snow, and is mixed with common salt in the proportion of two parts of ice, by weight, to one of salt, both are melted, and a temperature of 32° F. below the freezing point of water, i.e., 0° F., may be reached. This is the usual means of freezing ice cream and water ices. Three parts of snow mixed with four of calcium chloride will produce a temperature as low as –54° F.

CHAPTER XX

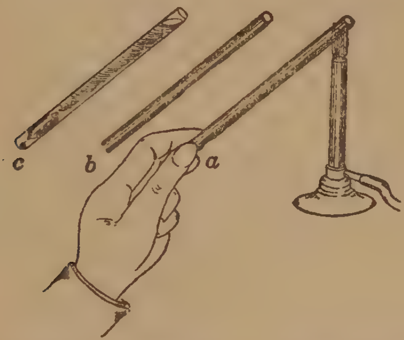
HOW HEAT IS TRANSMITTED THROUGH BODIES

IN the figure, (*a*) is a rod of copper one-half inch in diameter and six inches in length; (*b*) is a rod of wood of like dimensions; and (*c*) is a thin glass tube of the same diameter, containing water with a piece of ice held at the bottom by a leaden pellet. All are at the same temperature, say 32° F. If (*a*) is held at the lower end between the thumb and finger, and the flame of a burner is applied to the upper end, in a few minutes the entire rod will be heated and the lower end will be too hot to hold. If this operation is repeated with (*b*) moderate heating will slowly reach the fingers, but the rod may be held until it has been burned almost to the lower end; proceeding in the same way with (*c*), the water near the top, where the flame is applied, will be heated and may be made to boil vigorously, while the ice remains solid, unaffected except for the slight warmth it receives from the fingers.

In the first case heat traveled rapidly and in considerable quantity from the upper to the lower end of the copper rod; in the second, heat was transferred along the stick slowly and in small quantity; in the third case, apparently it did not traverse the water at all.

In the solid a heated molecule, imbued with greatly increased energy of motion, communicates its energy

to its neighbor by direct impact, and this one hands it on to the next, so that in a short time energy is led to the farthest portion of the body. This process is called "conduction"; energy is conducted, or passed on, through the body while the molecules remain in their own proper places. The composition of different substances is such, however, that some conduct heat better than others;



DIFFERENT SUBSTANCES AS CONDUCTORS OF HEAT

all metals are good conductors; wood, paper, and organic substances generally are not good conductors; liquids are very poor conductors, some hardly conduct at all, while gases are almost perfect nonconductors.

But heat will traverse liquids and gases by a different process. In the above illustration, if the tube of (*c*) were held at the top and the heat applied at the bottom, the liquid there would be heated, the ice melted, and the upper end of the liquid column would rise in temperature almost as rapidly as the lower end. The heated water is less dense and therefore lighter than the colder portion, and rises

through it; if (c) is inclined as in the figure, warm water will travel to the top of the tube just beneath the upper side of it, and the colder water will descend along the lower side, and a circulation is established. The heated molecules themselves go from the bottom of the tube to the top, and convey their energy with them. This process is called "convection," a term which means conveying or carrying along.

Convection is even more pronounced and rapid with gases than with liquids. So sensitive are gases to temperature change that it is difficult to get rid of convection currents in them. Where the circulation of the gas is impeded, however, it becomes an excellent insulator, and forms a good sheath around an object to prevent loss of heat or access of heat. An air jacket around a boiler prevents the escape of heat to a considerable degree, and if the walls of an ice house are filled between the inner and outer shell with air loosely packed with sawdust or tan bark, the ice is protected against melting in summer. This is precisely the principle upon which our clothing keeps us warm. A woolen garment, a blanket, or a coat of fur is very porous, but holds air imprisoned in its meshes. The finer and softer the fur, the more effective it is, for heat is conveyed or conducted through it very slowly. If ice, however, is to be used for keeping something *cool,* it must be remembered that the ice should not be kept from melting; the larger the quantity of ice melted, the more heat is taken from the air and other substances around it.

The quantity of heat that will be conducted through a body, a bar of metal, for example, depends upon

(1) The difference of temperature between the ends of the bar—the greater this difference, the more heat conducted.

(2) The length of the bar—the longer, the less heat conducted.

(3) The area of cross section—the greater the area the greater the conduction.

(4) The time the operation is continued—the longer the time the more heat conducted; and finally

(5) The nature of the substance.

With all the first four quantities alike in a number of different materials, the amount of heat transmitted will be different for the different bars. A bar of given size is tested by having one end in boiling water, i. e., at 212° F., and the other against ice, at 32° F., and observing the rate at which the ice is melted; every pound melted taking 142 B. t. u.'s.

The number of heat units conducted per second through a bar one square inch and one inch long, with a difference of one Fahrenheit degree between its ends, is the measure of its conductivity. Silver is the best conductor; almost seven times as good as iron; copper is next. Taking the conductivity of silver as unity, that of glass is .002; ice, .004; flannel, .00023; paper, .00030; water, .0014; air, .000056.

CHAPTER XXI

HOW HEAT IS TRANSMITTED THROUGH SPACE

THERE remains a third mode of transmitting or transferring heat. This occurs always in some measure from a heated body, but acts without the aid of molecules in transit, either to conduct or to convey the heat.

When we stand near a hot body we feel the heat from it. In front of an open fireplace the warmth is unmistakable, but we are not in contact with the fire, or with anything inserted in it; the air that is heated by it does not come to us, on the contrary the whole movement of the air is *toward* the fire, where it feeds the flame with oxygen, and the residual gas goes up the chimney. How then does heat reach us?

The process is called "radiation." It presupposes all space and all bodies to be permeated by a rare medium, the "universal ether," which is capable of transmitting vibratory motion in waves throughout itself. A wave of water, started by a stick from one side of a pond, will travel to the other side, and if the blows of the stick are repeated, waves will continue to cross the pond, although the water itself will not so travel. But a chip lying on the water at the farther side of the pond will be set in motion, and will rise and fall on the waves as long as their motion is maintained. The waves communicate kinetic energy to the chip. Now, the ether is believed

to be present in all bodies, as well as in the world space of interplanetary and interstellar regions, and the molecules of material bodies are enmeshed in some unknown wise with the ether, so that waves of the ether impart motion to the molecules of a body as the water waves impart motion to the chip.

"How is it," asks an inquirer, "that a person standing by a window, in a room, is warmed by the glowing sunshine that streams in upon him, although outside, that sunshine has passed through air that is bitterly cold?" Perhaps a mechanical illustration will make the explanation clearer. If water falls from a higher to a lower level, it can do work, and if it strikes against the vanes of a wheel it may propel machinery. If the vanes are moving just as fast as the water would move in falling freely, the water is doing nothing to drive the wheel, but to whatever extent its motion is checked, it will impart energy to the wheel. If, when the water leaves the wheel, it has no motion, all its energy has gone to drive the machine; if it still has velocity, that means kinetic energy, representing a part at least of the energy with which it began its descent; only that part which was taken out of it has gone into the wheel.

Sunshine is energy from the sun, transmitted across space in the character of vibratory motion in the universal ether. Until it is impeded by matter, this energy does not appear as heat. In material bodies the ether is less free and its motion is communicated in varying degree to the molecules among which it is entangled. Some bodies transmit the ether vibrations pretty freely — they intercept or absorb little energy, and are not greatly warmed by the sunshine; others stop off the motion and themselves take up the energy, or what is the same thing,

become heated. In no case is a body heated by the energy which *passes through it,* but only by that which fails to get through. Possibly some sunshine may have been intercepted by the air, and if so, the air was somewhat warmed by it; and so too, with the glass of the window; but certainly whatever portion fell upon the person had nothing to do with anything else, and if it did not pass through him, went altogether to light and warm him.

The ether, then, is the medium by which energy is transmitted across space from its source to the object receiving it. It is in this manner that the heat of the sun proceeds to the earth, or that of the glowing grate fire reaches a person standing on the windward side, no matter how cold the air itself may be.

When radiant heat encounters a material body, (*a*) it passes through the body, or (*b*) it is reflected from it, or (*c*) it is absorbed by it.

Only in the third case is the body affected by it; for clearly, the energy that passes through the body and leaves it, and that which is turned away from it, has not been expended upon it. These effects are produced in very different degrees by different substances. Those which permit heat to pass through them readily are called diathermanous; those which do not permit the heat to enter them are reflectors; and those which take in heat are absorbers. The same body may be a good absorber or a good reflector, depending upon the polish of its surface; if this is high, the heat will be reflected; if the surface is rough, the heat may be absorbed. But the body does not have both qualities, in a high degree, at the same time. Good absorbers are poor reflectors, and good reflectors are poor absorbers. A highly polished teakettle placed close to a glowing fire

heats but slowly, as the heat is reflected; but if put on a moderately hot stove it heats rapidly, for the metal is a good conductor, and through its unpolished base in contact with the stove it takes in heat readily. Every body radiates heat on its own account, but generally the best radiators are those which absorb heat freely.

The hotter the body from which heat is radiated, the more rapid are the vibrations of the ether transmitting the waves, and the shorter are the waves. Among the heat waves from the sun are many that are shorter than those that are emitted by the earth or by bodies upon it. Now, some substances that transmit short waves will stop long waves, or be impervious to them. Glass is such a substance. It permits the heat as well as the light of the sun to stream through it, because the waves are short, but it intercepts the longer waves radiated from bodies of ordinary temperature. Hence the interior of a conservatory or greenhouse is warmed by the rays of the sun, while little of the heat collected within escapes through the glass covering, even after the sun has gone down.

Clouds and water vapor in the atmosphere act in the same way as the glass covering of the greenhouse. The heat of the sun passes through readily and the earth is warmed. If the air is dry and clouds are absent, the earth radiates its heat into space freely after sunset, and the temperature falls quickly and sharply, as is often noticed at high elevations; but no dew is formed on cloudy nights, for the clouds constitute a blanket which prevents the loss of heat from the earth by radiation, and it does not cool down to the dew point. That there should be a snow line on mountains above which snow is

present the year round is to be attributed to the rapid radiation of heat from the earth where there are no clouds to blanket it, and eminent scientists have thought that it is largely if not wholly to this protective effect of the clouds and the atmosphere that we owe a temperature of the earth high enough to make our existence on its surface possible.

It is the province of science to develop these principles, and the business of the arts to apply them for the progress of civilization. Such applications are innumerable, and are being made continually, and a man's intelligence may safely be gauged by his appreciation of them. In small things as well as in large, these principles of heat are finding their place in our daily life.

The excursionist to-day hardly considers his equipment complete without his thermos bottle. This highly scientific article, first devised about twenty-five years ago, to keep liquid air, hydrogen, or other gases from volatilizing, has become a commonplace in the hands of users who have little appreciation of its scientific features.

It is a bottle within a bottle, the only connection between the two being at the neck. The space between them is a vacuum, the inner surface of the outer bottle and the outer surface of the inner being coated with lustrous silver. Supported in an outer casing of metal with a cushion of corrugated paper between it and its metal sheath, it is reasonably well protected against breaking. If a hot substance is put in the inner bottle, there is almost no passageway for heat to escape by conduction; there is nothing in contact with the inner bottle to carry off the heat by convection; its surface is highly polished and therefore radiates heat poorly, and what little

it does send off is returned by reflection from the second or outer bottle, so that very little heat is lost by this process. As a consequence the contents retain their heat a long time.

So also, if a cold liquid is put in, it will remain cold, because there is no more opportunity for heat to reach the interior from without than there is for the heat within to get out. The passage of heat through such a vessel is only one-tenth to one-twentieth as rapid as through a single-walled vessel, unsilvered.

The warming of buildings other than by stoves or open fires is usually from a furnace in the basement or lowest story, and the method is by hot air, hot water, or steam. In each of these, the heat is transmitted from the furnace and distributed through the building and rooms by convection. In the first, air is admitted into a space, an inclosure or jacket, enveloping the fire box, and this is directly heated by the fire and hot gases of the furnace. From the top of this hot air chamber, flues are led up to the various rooms where "registers" or openings are provided. The hot air rises and is discharged into the rooms through the registers, literally "conveying" heat directly from the furnace, the supply being continually renewed with fresh air from outdoors, flowing through the influx tube into the base of the air jacket around the fire box.

In the hot water system, instead of the air jacket, a corresponding chamber full of water is around and over the furnace fire. It is closed like a boiler. A pipe leads from the top of this to the uppermost floor, where it connects with (hollow) radiators; from these, return pipes connect with radiators on successive lower floors, the final return pipe enter-

ing the base of the water chamber at the furnace. The whole system of pipes and radiators is first *filled* with water from the mains or a tank, including an extra height of pipe to an overflow above the uppermost radiator, and then the main is cut off. The water, when heated, rises through the principal pipe to the highest radiators, flows through them, and as it cools, returns through lower ones, reentering the water box of the furnace at the bottom. A circulation is maintained which will be the more rapid with rapid heating in the furnace and rapid loss of heat to the rooms. The value of the system lies in the very high capacity of water for heat. A pound of hot water, in cooling one degree F., gives up one thermal unit. A radiator of moderate size may contain a hundred pounds of water, and if the water enters at 200° and leaves it at 190°, it will give up to the radiator 1,000 B. t. u.'s. This heat is communicated to the room by direct radiation and by convection currents of air that pass over the radiators. The same water is continually used, only a small addition being required occasionally, to replace loss from overflow and leakage.

In steam heating, regular boilers are heated by the furnace fire, and carry in them steam at a small pressure, perhaps five pounds per square inch, above the atmosphere. Like the hot water in the previous case, the steam rises and is admitted to the radiators throughout the building, entering them as steam at one end and leaving them as hot water at the other. The metal of the radiators is at a temperature below 212° F. and the steam in condensation gives out its latent heat of vaporization, which goes to keep the radiator hot. The hot water flows back to the boiler by return pipes, again to be converted

into steam and renew its circulation, or, if otherwise disposed of, more water is admitted into the boiler from the mains.

In the hot water system the radiators are heated directly by the water as this cools without change of state; in the case of steam, a fall of several degrees in its temperature would not accomplish much heating of the radiators, since the specific heat of steam is less than half as great as that of water, but for every pound of steam that is changed into water, 966 B. t. u.'s are supplied to the radiator, and this latent heat of vaporization becomes effective in heating the radiator upon the change of steam into water.

In the complex civilization of to-day, every inhabitant of a large city, whether he be high or low, rich or poor, learned or ignorant, shares, even if unconsciously, in the applications of physics to the very possibility, not to mention comfort, of living. Not only are the best facilities required for transporting food and fuel to the cities, but means must be employed to protect food products from decay, both before and after transportation. Storage of food, while objectionable if prolonged, is absolutely necessary for brief periods, and no other means has served this end as well as refrigeration. Large storage rooms can be kept at a low temperature by having their air in contact with metal surfaces, like coils of pipes, which are artificially cooled. This is as effective, in its way, as heating by means of coils or radiating surfaces kept hot by some circulating fluid. For refrigeration of this kind, besides cooling by expansion of compressed air, the vaporization of a volatile liquid, like ether or ammonia, is most common. Ammonia gas, at ordinary temperature, is driven by a compressor pump into a compression tank. In its

compression it is considerably heated. From the tank it is delivered into condenser pipes over which flows a thin layer of cold water. Under this cooling, the gas at high pressure liquefies. This also produces heat which is taken up by the water, and the liquefied gas is passed into a storage tank. It is all the time under high pressure, though now at a temperature not much above that of freezing water. From this tank, as fast as may be needed, the liquid is injected into a system of pipes in or around the room to be cooled. The pressure in these pipes is low; little if at all above that of the atmosphere, and the liquid is immediately vaporized with a severe fall of temperature, chilling the pipes to such a degree that the moisture of the air around is deposited upon them often in a beautiful white mantle of frost. The gas after expansion is led back to the compressor for a repetition or continuance of the process. This system is often used to cool the air of large auditoriums. Similar means are employed in the manufacture of ice.

In dealing with the latent heat of fusion we found that the reverse process, the solidifying of a liquid, was attended by the emission of heat. The like applies to the conversion of a gas into a liquid. For every pound of water that is changed into steam at atmospheric pressure, 966 B. t. u.'s are required, with no increase in the temperature of the steam above that of the water; with the slightest increase of pressure or diminution of volume, or with the slightest diminution of temperature, the steam will revert to water at the same temperature, and for every pound of steam thus restored to water, 966 thermal units will be set free. Liquefaction of a gas, like freezing of a liquid, is a warming process.

CHAPTER XXII

THE GREAT THERMODYNAMIC LAWS

THE most important fact concerning heat in its relation to other branches of science, and to practical affairs, is that it is one of the many forms in which energy manifests itself; and the greatest step in scientific progress in the nineteenth century was the establishing of this fact, along with an exact measurement of the numerical relationship between quantity of heat and quantity of energy in other forms. The first of these relationships to be established was that between heat and mechanical work. It is expressed in two formulas, known respectively as the First and the Second Law of Thermodynamics. The first law declares that *any definite amount of mechanical work is convertible into a definite quantity of heat, and, conversely, any given quantity of heat is capable of performing a definite amount of work.* The number of work units that produce one heat unit is called the "mechanical (or dynamical) equivalent of heat." In English measures, 778 foot-pounds produce 1 B. t. u. In the metric system, 425 gram-meters equal 1 calorie. Heat values, then, may be expressed in foot-pounds, or mechanical work in thermal units, and then are mutually convertible. As a practical example, suppose an engine that applies 15 per cent of the heat of combustion of coal to useful work, is employed to pump water from a reservoir to a height of 100 feet. If coal is used, of

which one pound liberates 14,400 B. t. u.'s in burning, how much coal will be required to pump 1,000,000 gallons (8,340,000 pounds) of water?

The work to be done is 8,340,000 x 100 or 834,000,000 ft.-lbs.; the heat from one pound of coal is 14,400 B. t. u.'s, and as every B. t. u. equals 778 ft.-lbs., the total work that can be derived from a pound of coal is 14,400 x 778, or 11,198,200 ft.-lbs. But of this the engine applies only 15 per cent or 1,680,000 ft.-lbs. The total weight of coal required therefore, is $\frac{834,000,000}{1,680,000}$ or very nearly 500 lbs.

The second law states that *it is impossible, by means of inanimate material agency, to derive mechanical effect from any portion of matter by cooling it below the temperature of the coldest of surrounding bodies.* This law is not so simple as the first, and has been cast in several forms: as, *it is impossible for a self-acting machine, unaided by any external agency, to convey heat from one body to another at a higher temperature.* In plainest terms it means that so long as a body is hotter than its neighbor, it can communicate heat, and doing that is transference of energy which will reappear as work done on the colder body; but heat will not of itself pass from a colder to a hotter body, and if work is to be done by heat derived from the colder body, it must be accomplished by the help of some other agent which, therefore, is the real source of the work.

Failure to accept this as a fact was the fallacy that led to disappointment in the attempt to develop liquid air as a cheap source of power. It was assumed that air in liquid form, in a boiler, would be converted into gas at a high pressure, simply by the heat of the atmosphere, thus wholly dispensing with

the fuel required for a steam engine. But to liquefy air in the first place requires mechanical work of compression, together with the expulsion and loss of much heat, so that, in the end, it requires as much work to bring air from a stated temperature and pressure to a liquid, as the latter can give out in returning to its initial state.

We have stated that some gases could be liquefied only at a very low temperature, and until it was possible to obtain such low temperatures, it was not really known that they could be converted into the liquid form. The obtaining of these extremely low temperatures is one of the great achievements of modern science. No interconversion of energy is more common than that of mechanical work into heat and the reverse. When air is compressed work is done by the engine driving the compressor, and the air is heated; and when compressed air is released and expands against any resistance, even if it be only outside atmospheric pressure, the expanding air does work, and its temperature falls unless heat is supplied to it from some extraneous source. This is equally true of any other gas. If, in addition to being under great pressure, the gas (say ammonia or carbonic acid gas) has been chilled by some freezing mixture and liquefied, then, upon the release of pressure, the liquid is first converted into gas with the absorption of the heat of vaporization, and this again is followed by a further reduction of temperature by the expansion of the gas. Now suppose such a gas as air or hydrogen is in a pipe at a low temperature and under great compression. Let this pipe be surrounded by another containing a liquefied or highly compressed gas, and let this latter escape by opening into a large chamber or to the

open air. The envelope of gas or liquid falls to a very low temperature, chilling the inner pipe to the point of liquefying, or even freezing its contents. In this wise all known gases have been liquefied, and nearly all have been converted into the solid form.

HEAT ENGINES: ENTROPY

By the efficiency of a machine is meant the ratio of the work it does to the energy expended upon it to make it do the work; and the efficiency of any combination is the ratio of the work that is delivered to the energy that is supplied. In the study of heat engines it is desirable to examine the power the engine develops when working at a given rate under a given gas pressure. The indicator attached to the cylinder accomplishes this. In the higher study of thermodynamics it is shown that the highest efficiency that a heat engine can possibly develop depends upon the range of temperature between which the gas (as steam) works, and the absolute temperature at which it is admitted to the cylinder. if t_1 is the absolute temperature of steam from a boiler, and t_2 the temperature of the steam discharged from the cylinder of the engine, the engine cannot attain a higher efficiency than $\frac{t_1 - t_2}{t_1}$.

Now with reference to its heat and temperature, every body is in a condition that is changed by the addition of heat to the body or the subtraction of heat from it, and the extent to which this condition is altered depends upon the temperature of the body at which the change is made, as well as upon the quantity of heat added. The change itself then is measured by the ratio of the quantity of heat, h, added or subtracted, to the absolute temperature, t,

of the body. This condition of a body is called its entropy, and the change of entropy is the ratio h/t. When a body at temperature t_1 parts with q units of heat, its entropy is diminished by q/t_1; if this heat is communicated to another body at temperature t_2, which is necessarily lower than t_1, its entropy will be increased by q/t_2, which is greater than q/t_1, and the total entropy of the two bodies is increased by q/t_2-q/t_1. As this may be extended to bodies throughout the universe, it indicates that the total entropy is rising, which will continue to be the case so long as some bodies are hotter than others. This rise of entropy in a system of bodies accompanies a decrease in availability of heat in the system to do work, for it means an equalization of temperatures, and heat is available to do work only by transference from one body to another. We have just seen that the second law of thermodynamics is to the effect that without difference of temperature heat will not so pass. A universe of bodies all at high temperature would not do as much work among themselves by the great quantity of heat they possess, as they would do if of unequal temperatures, even though their aggregate amount of heat was much smaller. It is possible, by means of the heat applied to a gas, and the temperature produced, to arrive at an estimate of the work an engine can perform, through the entropy of the working substance, instead of the pressure that is produced.

A pound of good coal liberates about 15,000 B. t. u.'s by combustion. The best type of steam engine and boiler will not return more than 17 per cent of this in work. As one B. t. u. equals 778 ft.-lbs., this would be about 2,000,000 ft.-lbs. Suppose we wish to know how much coal would be needed for

such an engine to pump 1,000,000 gallons of water a height of one hundred feet. One gallon weighs 8.345 pounds; 8,345,000 pounds of water are to be raised 100 ft.; that would be 834,500,000 ft.-lbs; and as the engine gives out 2,000,000 ft.-lbs. for one pound of coal the total amount of coal required for the above work is $\frac{834,500,000}{2,000,000}$, or about 417 pounds.

THE SUN'S HEAT ON THE EARTH

The heat, and consequently the mechanical power, received on the earth by direct radiation from the sun far exceeds that from all other sources combined. It has been the subject of much recent investigation and has been found to average about 7.4 B. t. u.'s per square foot per minute, on a normally exposed surface above the atmosphere, which is reduced about one-third at sea level by atmospheric absorption. One square foot on the earth would be an exceedingly small spot on a spherical surface of which the sun was the center and having a radius equal to the distance from the sun to the earth, or 92,000,000 miles. If the radiation was equal all over the sun's surface, it would mean emission of 7.37 B. t. u.'s upon every square foot of such a spherical surface, or from every square foot of the sun's surface enough heat to burn 1,400 pounds of coal per hour. The actual temperature of the sun has been computed to be from 5,000° C. to 6,000° C.

While the figure 7.37 B. t. u.'s is the average value of the so-called "solar constant," it is not constant throughout the year or from all portions of the sun's surface. A publication by the Smithsonian Institution states that "the existing abnormal changes, which we call *weather*, have their origins chiefly in the *variations of solar radiation*."

CHAPTER XXIII

SOUND

THE term sound is used in two senses; one to express a physical action external to ourselves, the other to express the sensation that makes us aware of such action, and reacts upon us in some sort of emotion or response. It is mainly in the former of these senses that sound is considered in physics and is studied as to its production, its transmission, and its perception.

A sounding body is always a vibrating body, and while it is conceivable that a body might vibrate without producing sound, the only change that is needed to convert a silent body into a sounding one is to put it into vibration. But there will be no communication of the sound, nor any physical manifestation of it, unless the vibrating body is immersed in, or is in contact with, an elastic medium upon which it can impose its movement, and send it on to a recipient. A bell set ringing under the receiver of an air pump is heard plainly at first, but as the air is exhausted the sound becomes fainter, and with a high vacuum it is no longer audible, because the elastic medium, the air, is no longer present to convey the vibration.

The vibrating body that is producing sound may be a solid, as a bell; or a liquid, as a sheet of falling water; or a gas, as a column of air in a pipe. In many instances, especially with solids, the vibration

is made quite apparent by the knocking away of any light object that rests against the sound-producing body.

Vibratory motion, whether of a large body or of a minute particle, is a passage through a series of positions, and a return through them, always in the same length of time, the total time required in making the complete passage both ways being called the period of the vibration.

If a single particle is set vibrating, it communicates its motion to its neighbors on every side, and intermolecular action of the vibrating substance carries the disturbance throughout it. The figure assumed by all the particles that are disturbed successively during the period of one vibration is a *wave,* and the distance the disturbance travels in any one direction, in one period, is the wave length. In the case of water waves, the force that controls the rise and fall of the particles is that of gravity, but in the wave propagation of sound the motion of the particles is controlled by the elasticity of the medium through which the sound waves are traveling. In their simplest character waves are of three types, resulting from the direction of the periodic motion of the particle.

Let us consider a single line of particles in a sound wave. In water (the liquid type), a particle driven suddenly downward is so influenced by the drag of its neighbors, that both it and they are carried around in circles instead of to and fro, and this occurs successively all along the line, each particle moving a little later than its predecessor. As a consequence, when the first of a series has just completed its circular orbit, *somewhere* along the line there is one just beginning, and in the interval the

particles occupy all the successive positions in a vertical circle, from the highest to the lowest, and the complete line of particles will have a sinuous form.

The figure illustrates the formation of sound waves in air, and their progress to a hearer. When the prong of the tuning fork is in one extreme position, say at the right, and begins its movement to the left it starts a compression which progresses a certain distance while the prong is moving to the left. The prong then swings in the opposite direction,

SOUND WAVES

Formation of sound waves and progress from tuning fork to ear of hearer

causing a rarefaction immediately after the condensation, and the rarefying will continue while the prong swings back to the starting point. During this time the condensed condition has advanced as far is it did while the compression was in progress, and the rarefied condition extends just as far after it. Each of these conditions extends half a wave length, and the two, making a whole wave length, reach as far as the disturbance travels in the period of one vibration, the vibrations of the air particles being the same in number per second as those of the fork. If, in one second, the number of vibrations is n, at the end of one second there will be a series of n waves from the fork outward, and if each wave

is l feet long, the farthest one will be nl feet from the source of the waves. That is the distance the sound traveled in one second, or the velocity of sound.

Newton demonstrated that the propagation of sound waves through an elastic medium depended wholly upon the *elasticity* of the substance through which the waves travel, and its *density;* and that the actual speed with which they move through any medium is the square root of the quotient obtained by dividing the elasticity by the density.

With solids and liquids neither the elasticity nor the density is altered appreciably by any moderate change of temperature, and the velocity of sound in them is practically the same at all ordinary temperatures. But with a gas the case is very different. At any temperature, if that temperature is maintained, the elasticity of a gas is equal to the pressure; therefore, in open air if the barometric pressure is the same at one temperature as another, say 30 inches, the elasticity will be the same, but the density will vary sensibly with a difference in temperature, decreasing by $\frac{1}{491}$ part for every degree above 32° F. At 32°, and standard pressure, the density of air is .0808 pounds per cubic foot, the elasticity 2,116 pounds per square foot, and according to theory the velocity of sound in air at that temperature should be 918 feet per second. But when the velocity is actually measured, as by observing the interval between the flash and the report of a gun situated at a known distance, it comes out at 1,090 feet per second. This exceeds the theoretical value by 162 feet per second, or nearly one-fifth, and the disparity was a stumblingblock to physicists until Laplace pointed out that the source of the mistake lay in the value

of the elasticity. When air is compressed it is heated, and upon rarefaction it falls in temperature. So, in the compression and rarefaction caused by sound waves, unless the heat is carried away or restored as fast as the air is heated or cooled, the elasticity is greater than it would be at a constant temperature. Laplace showed that by making a proper allowance for this change of elasticity, the calculated velocity would be 1,086 feet per second, agreeing very closely with experiment. Although the pressure is one of the factors in determining the velocity of sound in a gas, inasmuch as any change of pressure changes the density in the same proportion, the velocity of sound is not altered simply by a change of pressure.

Since the velocity of sound depends wholly upon the medium through which it is passing, and in nowise upon the nature of the sound itself, it follows that all sounds, high or low, strong or weak, simple or complex, will travel at the same rate. If this were not so, a musical performance that has a perfectly definite order of succession in its tones to an auditor near by would be confusion worse confounded to a listener at a distance, for some of the sounds would require a longer time than others to travel from the orchestra to him. The fact that there is no such confusion is evidence that the sounds all travel with the same velocity.

The different velocities of sound in different media lead to some extraordinary results. If a listener puts his ear to the steel track of a railroad, a blow upon the rail at a considerable distance away will be heard twice; first, almost immediately by transmission through the metal, and again a little later, through the air.

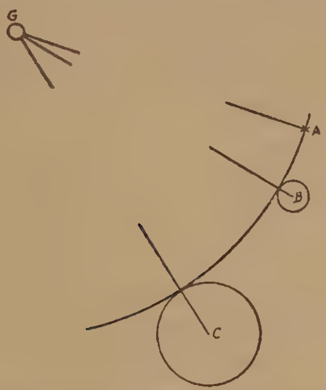
It is almost disconcerting when watching a man several hundred feet away, chopping with an axe, to hear the sound of the blow when the implement is about reaching its highest point in the air, instead of at the instant when the blow is struck.

An obstruction in a pneumatic mail tube may be located by discharging a pistol in front of a membrane stretched across the open end of the tube, and observing accurately when the pulse that travels along the pipe is returned to the open end after reflection from the obstruction. In one instance, with the temperature of the air in the pipe 70° F., the time was 2.2 seconds. The velocity of the sound wave was 1,130 feet per second, and in 2.2 seconds the pulse traveled 2,486 feet; the obstruction, then, was probably one-half that distance or 1,243 feet from the end of the tube. It was actually found within about two feet of the point thus indicated.

The air brakes on a railroad train are operated by compressed air contained in a cylinder under each car. A pipe leads the compressed air from a tank in the cab of the engineer to all the air-brake cylinders. To apply the brakes the engineer turns a lever that discharges air from this pipe, and *releases* the air pressure in it. This at once permits the pressure in the several cylinders under the cars to act, thus putting on the brakes. If the train is 500 feet in length, the pulse of rarefaction, started from the engine cab, travels along the pipe with the velocity of a sound wave, and applies the brake on the last car within less than half a second after the engineer throws the lever. No human brakeman could be so prompt. In fact it would require exactly the same length of time for the sound of the signal whistle to reach him before he began to act.

At the temperature of 32° F. the velocity of sound in air is 1,093 feet per second; in water, 4,700; in aluminum, 16,900; in iron, 16,240; in wood, along the fiber, 13,000 (average); across the fiber, 4,500 (average).

A very famous modern instance of the uses to which a knowledge of the velocity of sound may be put is the discovery by the French of the location of the long-range gun with which in 1918 the Germans



GUN LOCATED BY VELOCITY OF SOUND

bombarded Paris from a distance of 70 miles. The Germans had concealed the gun from aviators by skillful camouflage, but their efforts to confuse its sound by discharging other batteries at the same time were not so successful. Among other means used to determine its position was the method illustrated by the diagram above.

The discharge of the gun at G, an unknown location, is heard at A, a known location, at say exactly 10 o'clock. The same report is heard at B just three seconds later, and at C twelve seconds after it was heard at A. In three seconds sound travels 3,300

feet. On a map, drawn to a large scale, describe a circle about B as a center, with a radius of 3,300 feet. *Somewhere* on the circumference of that circle there must be a point that is at the same distance from the gun as A is, and this point lies on the line BG. In twelve seconds sound travels 13,200 feet. With a radius of 13,200 feet describe a circle about C. Somewhere on this circle, too, there must be a point at the same distance from G as A. If, then a large circle is drawn passing through A and just touching the circles drawn about B and C, the center of this large circle must mark the location of the gun. The method was greatly elaborated and extended by the American Sound Ranging Service in France to locate numerous other heavy guns of the enemy. In one instance as many as seven points were electrically connected with a central station where the time the sound reached the several points was recorded accurately by chronographs, and from these records the position of the guns was determined. The results were found in some cases to be correct, within fifty feet, for guns ten miles distant.

CHAPTER XXIV

SOUND AND HEARING

THE process of hearing is physiological as well as physical. The sensation is due to a stimulus of the auditory nerve, and this may be produced by various means. One may hear when there is nothing to be heard. A humming, buzzing or ringing in the ears is a common experience, though it is not occasioned by any noises or sounds external to the person. On the other hand, no sound, however penetrating, will be heard if it is not conveyed to the brain, the seat of its perception. The usual stimulus of the auditory nerve is through the outer ear, but not necessarily so. The inner ear contains a liquid that is capable of vibration in any degree of complexity, and in the liquid are a large number of threads or fibers, attached either to the walls of the chamber or to a so-called basilar membrane that forms a partition in it. These fibers are termini of the auditory nerve, and their free ends, floating in the liquid (as also the basilar membrane itself) respond to any movement in the liquid. This movement is thought to be the stimulus to the nerve.

Any cause, as inflammation, shock, or disease, that injures this ciliated membrane, or hardens it, or otherwise reduces its sensitiveness impairs the acuteness of hearing.

The outside disturbance constituting the physical sound may reach the liquid by various channels. The drum of the ear has been commonly supposed to be

the chief medium, but the bones, especially those of the head, may also be effective. A flexible fan pressed against the teeth makes a good sounding board, and is a distinct aid to hearing.

A single stroke or tap, or a shock in the nature of an explosion, will be perceived as a momentary sound, and if taps or strokes occur at intervals they will be perceived separately, until, with increasing frequency, the intervals become too brief for us to distinguish between them. The sounds then blend in one sensation, and a continuous tone is heard. The slowest rate of vibration at which a sustained tone is recognized varies with different individuals, being in some instances as low as sixteen per second, but it is seldom lower than twenty-four. In the other direction, when the frequency becomes exceedingly high, the organ of hearing fails to respond to it, and the sound cannot be heard. With human beings, this upper limit of audition is from 20,000 to 30,000 vibrations per second. It is probable that some insects and other creatures of the animal world may be able to distinguish sounds that are far above the limits of those which the human ear can perceive.

A sound of 20,000 vibrations per second would have a wave length in air of 1/20,000 of 1,100 feet, or about two-thirds of an inch, while the wave length of the gravest sound distinguishable, say of twenty-four vibrations per second, would be 1/24 of 1,100 feet, or about forty-six feet; more than eight hundred times the minimum length.

The range of responsiveness by the ear in respect to intensity of sound is no less wonderful than in respect to pitch, far exceeding the sensitiveness of the eye in its functions.

If a disk is perforated with a ring of holes, and set rotating, a jet of air from a nozzle in front of the holes will produce a series of puffs as the air is alternately stopped or permitted to pass through. Every puff is a condensation and rarefaction, and they may be made of any frequency by regulating the speed of the rotating disc. When they reach a rate of fifty or sixty per second they are perceived as a sustained, low, humming sound, which becomes higher as the recurrence of the puffs becomes more rapid, until, when the rate is a thousand or more per second, they emit a high, piercing note. Such an instrument is a *siren.* On steamships and in coast service for fog warnings, the note is produced by blowing steam instead of air through the orifices.

With slight force propelling the air from the nozzle, the note will at no time be very loud, but will pass through every stage from *low* to *high.* With a strong jet of air the sound will be stronger than before, but with precisely the same progress from low to high. The lowness or highness of the note is termed its "pitch," and is determined solely by the number of vibrations per second. This number is called the "frequency," and the time required for one vibration is the "period." A note of any frequency, high or low, may be so soft as scarcely to be heard, or so loud as to be deafening.

When the edge of a card touches lightly the teeth of a rotating wheel, a succession of separate taps is heard; as the speed of rotation is increased the taps become more frequent, and at about a hundred per second, they are no longer recognized separately, but become a continuous sound of low pitch. This rises with increased frequency until, as with the

siren, a shrill, piercing note is emitted, painful to the ear. The hum of gear wheels in rapid motion, the singing sound of machinery in general, are phenomena of this same character.

Since the pitch is determined by the rate of vibration, it is measurable, and may be fixed with mathematical precision, and any two notes may be compared definitely as to pitch. The ratio of the frequency of one note to that of another is called the "interval" between them, a ratio higher than unity meaning a rise in pitch, and a fraction less than 1, a lower pitch. When the interval is 2, or 1-2, the higher note is said to be an *octave* above the lower in pitch. The term "octave" is used because such a note is the eighth one in a series now commonly recognized and adopted as a natural scale of musical intervals.

THE MUSICAL SCALE

The eight notes of the scale have seven unequal intervals, which result from tones that occur in an order of succession developed from the ratio of the numbers 4, 5, and 6. Those particular relative frequencies, along with the octave, generally produce the most agreeable sounds. Why this combination should be natural, or agreeable, we cannot tell, though it has been the subject of much speculation. It characterizes the most highly civilized and artistic peoples, but some Eastern nations and some savage tribes find more pleasure in other relatives values. Three notes whose rates of vibration are as 4 : 5 : 6 constitute a "major triad." For these, the two increasing intervals are 5/4 and 6/5, and the last of the three is 3/2 the first; descending they are 5/6, 4/5 and 2/3. A series of any degree of complexity may be built up, but if we begin with a note of *any*

frequency and call it the unit, or 1, these ratios will at once give us the three notes of the frequencies 1, 5/4, 3/2; 2 being the octave. If we begin a new series with the last of these three, applying to it the same relative rates, that series will be represented numerically by 3/2, 3/2 x 5/4, 3/2 x 3/2, or 3/2, 15/8, 9/4, the octave below the last being 9/8. These may be arranged in combination with the former series, thus: 1, 9/8, 5/4, . . . 3/2, . . . 15/8, 2. If we were to consider the octave 2 as the last of such a triad, the three descend as the numbers 2, 2 x 5/6, 2 x 2/3, or 2, 5/3, 4/3, these being as the numbers 6, 5, 4; and these fit in the series between 1 and 2. Thus we form a series upon the same fundamental ratios with eight notes whose frequencies, compared with the first of the series, are 1, 9/8, 5/4, 4/3, 3/2, 5/3, 15/8, 2, and these constitute the octave mentioned above. When the eight successive notes have these relative rates of vibration they form a *natural* or *diatonic* scale. If we examine the intervals from each note to the next, they are found to vary somewhat, being:

Successive notes, 1, 9/8, 5/4, 4/3, 3/2, 5/3, 15/8, 2;
Successive intervals, 9/8, 10/9, 16/15, 9/8, 10/9, 9/8, 16/15,

a rise in five places of one-eighth or one-ninth, and in the other two of one-sixteenth. The larger intervals are called whole tones, the smaller half or semitones. So far as concerns recognition of the sounds by the ear, there might as well be half-tone intervals throughout the octave, and that would mean the insertion of notes between the first and second, the second and third, the fourth and fifth, the fifth and sixth, and the sixth and seventh. There would then be twelve steps from the first note to its octave.

In music, the notes are designated by the first seven letters of the alphabet, the natural scale beginning with the letter C. This is usually about the middle of the keyboard of a piano. The letters to write over the above series of successive notes would be C, D, E, F, G, A, B, c. A half-tone inserted makes the note below it "sharp" and is marked ♯, or the one above it "flat," marked ♭. If all half-tones were equal, C♯ and D♭ would have the same pitch, but that is not possible with the natural scale. If we took 16/15 for a half-tone, 16/15 of the beginning note, or 1, is more than 15/16 of the second note or 9/8: i. e., C♯ is higher than D♭.

If absolute numerical values were given for the pitch of the notes according to the natural intervals, beginning the scale with C, then those numbers would not make the correct intervals if we wanted to begin with C♯ or D. An instrument with fixed pitch for each key that is struck, like a piano, or organ, would require an enormous number of keys and strings or pipes, to make music with true intervals in different "keys," i. e., starting the octave with different frequencies as the keynote. With an instrument like a violin, on which a note of any pitch may be produced, every piece of music can be played in true intervals; on a piano it cannot.

To escape this difficulty, scales have been adopted in which some of the intervals are slightly false. A scale thus altered is called a "tempered scale." Various temperaments have been tried, but that in general use to-day makes all the twelve intervals in the octave equal to one another. Since the last note of the octave is the first multiplied by 2, the rate of vibration for each note must be that of the preceding one multiplied by the $\sqrt[12]{2}$, or 1.059. That makes

some of the notes a little too high and others a little too low, the actual comparison being as follows:

	C,	D,	E,	F,	G,	A,	B,	c
Natural Scale	1,	1.125,	1.25,	1.333,	1.5,	1.667,	1.875,	2
Equal temperament,	1,	1.12,	1.26,	1.325,	1.498,	1.682,	1.882,	2

"Monotone" means one-tone, and conversation or music that is not varied in pitch is monotonous and soon becomes tiresome. All modulations in pitch of the human voice, the songs of birds, and of music in general, are made in intervals that are clearly definite numerical ratios of the vibration frequencies of the notes uttered.

DOPPLER'S PRINCIPLE

If sound waves, emitted from a fixed source, with a definite frequency, traverse quiet air to a listener who is also stationary, he will receive the same number of waves per second that the body is emitting. If, however, the listener is approaching the source of sound, he will receive the waves faster, for he will encounter not only those which he would have received had he remained stationary, but will pick up some on account of his own progress toward the source of the waves. To him the pitch of the sound is raised. If his movement toward the sound is as rapid as the sound's travel toward him, he will double the number of waves per second, and the note will be an octave higher. If he were receding from the source he would receive fewer waves in proportion to the speed with which he is traveling, and the pitch would be lowered. Similar effects result if the observer is stationary and the source of sound is approaching him or receding from him.

If the note were loud and distinct and its source stationary while he drew toward it at the speed of

sound, say 1,100 feet per second, or the least bit faster than this, the note that he would perceive would be steady, but of a pitch an octave higher than if he and the sounding body were both stationary; but at the instant when he passed the sounding body, the note would drop *out of hearing;* he would leave it behind faster than the waves pursued him, and no sound would reach him. The effect is easily observed by a person standing on a station platform while a locomotive rushes past with its whistle blowing. The drop in pitch as the whistle passes is very noticeable. Here, if the engine were traveling with the speed of sound, the apparent frequency would be only one-half the actual, and the note would drop an octave in pitch. Various modifications of the change in the note are found if the air between the source and the observer is moving in either direction. In undisturbed air, if both source and observer are moving, there is no change in pitch so long as the distance between them is not altered. This change of pitch (or frequency *perceived*), is known as "Doppler's Principle"; it has been applied with interesting results in connection with waves of light, to determine the speed with which stars are moving toward our solar system or away from it.

If wind is blowing over the surface of the earth, in general the upper strata of air move faster than the lower, and the disturbance of the air representing the frontal progress of sound in the direction of the wind will move forward faster in higher regions of the atmosphere; consequently the sound front has an inclination that slants the sound downward in the direction toward which the wind is blowing, and upward in the opposite direction. In the former case, it may even happen that at a certain elevation, the

sound traveling in the direction of the wind would cease to rise, and would not reach a listener at a higher level. A precisely similar occurrence is found in the case of light.

INTENSITY; LOUDNESS

The intensity of a sound should not be confused with its loudness. The former depends upon the energy of vibration in the medium conveying the sound to the ear; the latter, upon the responsiveness of the machinery of hearing. If this is in poor working condition, vibration of given energy may make little impression upon it and the sound may scarcely be heard; the next day vibrations of the same energy may so affect the ear as to produce a loud sound; even less intense sound (vibration) may produce louder sound (sensation). Now the waves of sound from a single source are expanding shells of air, spheres around the source as their center; in these successive shells the energy is distributed through an ever-increasing mass of air, and consequently the energy of a single vibrating particle becomes less, decreasing as the square of the distance increases. Also, at any point, the source or elsewhere, the energy of vibration is directly proportional to the square of the amplitude, the amplitude being the *distance* which the vibrating particle swings on either side from its neutral position.

In general, however, with the ear in a constant condition, good or bad, more intense sounds are louder, though not in an assured or definite proportion. It is not practical to compare the sensations as definitely as the mechanical energy of vibrations.

So exquisitely sensitive is the ear to rapid alterations of density in the air, that these will produce an

audible sound when very slight indeed. Changes of density, or condensations and rarefactions, are large only when the air particles vibrate with an amplitude of a sixteenth of an inch or more, but the ear can perceive these changes when the amplitude is as small as one-half of one-millionth of an inch, and some tests have indicated a sensitiveness several times greater than this.

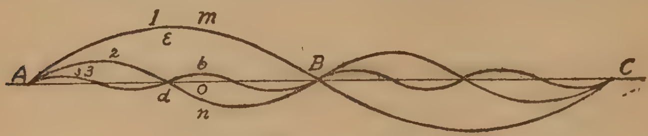
CHAPTER XXV

SIMPLE AND COMPOUND TONES

SOUNDS whose vibration rates are as the simple numbers 1, 2, 3, 4 are called harmonics, the lowest being the fundamental and the others overtones. A body will naturally fall into a definite rate of vibration, depending upon the way in which the material composing the body is distributed, and its elasticity. The tone that is produced by this natural rate of vibration is a fundamental tone; but besides vibrating at this rate, the body may break up into parts, which themselves vibrate more rapidly, and produce higher tones at the same time that the body is emitting its fundamental. All such higher tones are overtones, but they are not necessarily harmonics, or simple multiples of the fundamental. A tone of but one vibration-frequency is a "simple" sound; when the sound results from several rates together it is "compound," the separate constituents being "partial" tones.

Let a horizontal slender rod be clamped at one end and set vibrating in a horizontal plane; the free end swings to and fro above the table. If a pencil or stylus be attached to this end, and a paper be drawn longitudinally under it as it vibrates transversely with every complete vibration the stylus will trace a sinuous line, like No. 1 (A). This is the conventional representation of a wave; AC is the wave length, and *d e* the amplitude of vibration.

If, at the same time that the rod was thus vibrating at its fundamental rate, the two halves were vibrating as segments twice as rapidly, and another segmental division was producing four waves in the period of the fundamental, all with different amplitudes—these three sets of vibrations, if they could



(A) SIMPLE WAVE FORMS

be recorded separately, would produce tracings like Nos. 1, 2, and 3 (A). But when all the vibrations are in progress at the same time, the free end will at any instant be in the position resulting from the combination of the several movements. The three sets of waves may be compounded for every point along the axis AC, and when all the resulting points are located they will form the ungainly curve in (B), and this is the tracing the vibrating end would

(B) TRACING ACTUALLY MADE BY POINT VIBRATING AT DIFFERENT RATES

actually make with a stylus. Figure (C) shows the record obtained by the author of the fundamental tone of a tuning fork making 320 complete vibrations per second, along with an overtone that the fork was emitting at the same time. By actual count it is seen that the latter gives twenty-five vibrations

to four of the former, or just above six to one. Four times the fundamental would be the note just two octaves above it; six to one would be three halves of that, or the fifth note in the third octave, as previously explained, and this overtone is very slightly higher.

STATIONARY WAVES, NODES AND LOOPS

Not only solids have a fundamental rate of vibration, and overtones; the same is true of liquids and gases. Since solids can sustain a transverse strain, or have shearing elasticity, they can vibrate transversely, even though they impose longitudinal vibrations, and consequently waves of condensation and

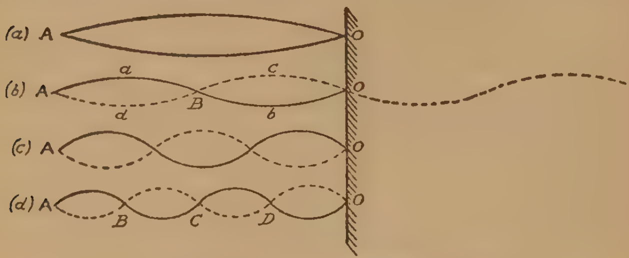
(C) TUNING FORK RECORD

rarefaction, upon the air. Gases cannot resist a shearing stress, and their vibrations as well as their waves are necessarily longitudinal.

A solid may have a definite size and shape which it will retain; a mass of gas (and we may use air as a type) can only have a prescribed form by being inclosed within a properly proportioned vessel, and the freedom of movement of the air is then restricted by the walls of the inclosure.

By inclosing air in a pipe, we have a column, or elongated body, of gas, whose vibrations and waves may be compared in many respects with those of solid rods or of strings. In all cases, whether the vibrating particles move in the same line along which the waves are traveling, or across it, each vibrating particle moves back and forth through a mid-position.

If an elastic cord, A O, is fixed at one end, drawn moderately taut, and shaken at the other end, by properly timing the movement of the hand, the cord will take the form of (*a*). With twice as rapid movement it will assume the form of (*b*), in which B, as well as A and O, is stationary. All the particles of the cord continue to move across the line AO, but the wave form is reversed. By reflection of the wave from O, the cord takes on a form as



VIBRATION OF AN ELASTIC CORD

if another set of waves were being returned through that point. In (*b*), AaBbO is formed between A and O. In the time the disturbance of the cord moves from A to O, a particle makes a complete movement in its path of vibration, across and back. In (*a*), A and O are stationary because, being at the ends of the string, they are held in position; if both ends of the string were fastened to rigid supports and the string were plucked in the middle, it would vibrate in the form of (*a*). Here the particle at the middle of the string has the largest movement. But to have an intermediate point between A and O at rest while the string is vibrating it is not necessary to have that point secured to some object; if any particle tending to move in one direction is met by an equal countertendency to move in the opposite

direction, it will remain at rest. In (*b*), BbO is swinging up into the position BcO while AaB is swinging down into the position AdB; B is a point of counteraction, and moves neither up nor down. The effect is the same as if the train of waves along the cord from A were met by a like train.

If the rate of vibration is such that in one period the wave only travels half the length of the string, there are two waves, AC and CO, (*d*), between A and O, and the string will vibrate in four segments, B, C, and D being points of rest or of minimum movement. These points, as also A and O, are called *nodes*, and the wide parts *loops* or *ventral segments*. From node to node, or from loop to loop, is a half wave length. At the loops there is the greatest movement. The rate of travel of the wave along a string of given length and material depends upon the tension, and by adjusting this the cord may be made to vibrate in any number of segments. While the body is thus vibrating, the waves are really traveling along it in opposite directions at the same time, but they appear to be locked or tied in position ("node" means knot), and so are called "stationary" waves.

CHAPTER XXVI

INTERFERENCE OF SOUNDS

IT is the function of sound to be heard. Sound is the direct antithesis to silence, and it would be natural to expect that two sounds together could be heard more readily than either one alone. Yet the question is sometimes asked: "Can two sounds produce silence?" and the answer is: "Yes." And this is true, no matter how loud the sounds may be; but one must be as loud as the other. This is a phenomenon that is known technically as "interference," and is much more often in evidence than is commonly suspected.

When two trains of waves meet in such relative positions as to the vibrating particles that the crest of the wave in one train coincides with the crest of the other, and trough with trough, the combined effect will be to heighten the crest and deepen the trough, and there will be a reenforcement of the wave phenomenon, and of its effects. If the waves unite so that the crest of one coincides with the trough of the other, there will be interference, and if the two are equal in amplitude there will be destruction of the waves. In light waves that would mean darkness; in water waves, a placid surface; in sound waves, silence. While stationary waves and the phenomena of interference are most easily represented with transverse waves, they occur just the same in waves of condensation and rarefaction, in

which the vibrations are longitudinal. The reenforcement or interference may be partial or complete, momentary or continuous, at one spot or over an extended region.

If two sources of sound were sending out waves at the same rate, but were so vibrating that a condensation of air from one reached a listener at the same instant as a rarefaction from the other, he would hear neither, though each was plainly audible when sounding alone. If they were of equal intensity, the two sounds would produce silence. It would be difficult to set two bodies thus vibrating in exactly opposite phases, but the effect is easily observed by a gradual change. Suppose two sounding bodies side by side, say two tuning forks, are almost but not quite in unison, one making 256 and the other 257 vibrations per second. At some instant they will both be producing a condensation in a given direction with a rarefaction following from both together. The effect of this is greater than it would be from either fork alone, and there is reenforcement of vibration of the air and a louder sound. But one fork is gaining on the other and in half a second it will be half a vibration ahead. It will then be emitting a rarefaction with the other's condensation, the two will interfere, and if of equal intensity will nullify each other and there will be no sound. In another half second the faster fork has gained another half vibration, and the two are again sending out waves in the same phase, and once more the sound is reenforced. There will be a succession of swellings and subsidences (or extinctions) of sound, one of each every second, as long as the forks continue to vibrate. These changes of sound are known as "beats." If the forks differ by two vibrations per

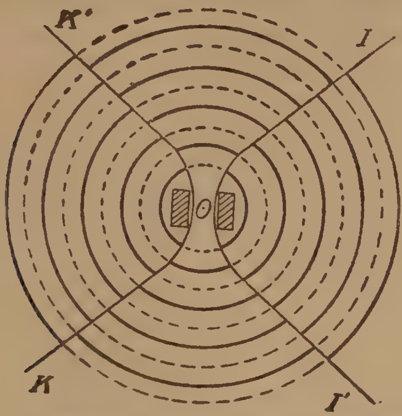
second, there will be two beats per second, and so on. When the beats are very rapid they make a throbbing of pulses that may acquire a frequency sufficient to produce the *sensation* of a low tone called a "beat-tone."

A policeman's whistle is a short double pipe of high pitch, one part producing a note of ten to fifteen vibrations more per second than the other. The two pipes have a common mouthpiece and when the whistle is blown they sound together in a shrill, tremulous note, the trill being the beats. It sounds as if there were some vibrating object in the pipe, but it is all done by the air.

If the notes differ by only one vibration in several seconds, both the intensified sound and also the silence or the diminished sound will persist for a correspondingly long time instead of being only momentary. Two organ pipes that are not quite in unison sometimes do thus act together without emitting any sound at all to the audience. A single tuning fork admirably illustrates this phenomenon, which anyone can easily experience for himself. The figure shows the vibrating fork, "end on." As the prongs separate they send out right and left a condensation of air, and up and down a rarefaction, either of which, alone, would make a ring of its own character about O. In reality those two kinds of ring meet at four points. The return swing of the fork in like manner produces a rarefaction right and left, and a condensation up and down, again with four points of interference; and this extends throughout the region around the fork as far as it can be heard. In the figure the full lines mean condensations and the broken ones rarefaction, and there are four lines or surfaces of inter-

ference from O toward I, I′, K, and K′, on which the fork is not heard.

If a vibrating fork is held vertically beside the ear, and slowly turned about its stem, its sound will die out and revive distinctly, four times with every



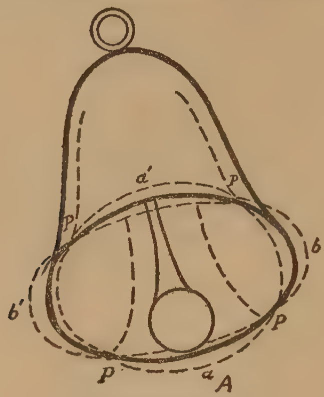
A VIBRATING TUNING FORK—END ON

It is silent along the lines *I K, I′ K′*

complete revolution of the fork; the extinctions are when the ear is on the line IK or I′K′.

A bell sounds in the same manner. If the circular rim of the silent bell, illustrated, is struck by the clapper, say on the inner side at A, the elastic metal is driven into the form of the dotted oval figure a a′, which immediately changes to b b′, and passes continually from one of these forms to the other. Vibrating in four segments, there are four nodal points P, in the edge, like those in the preceding figure. This would be its normal way of vibrating, though it might divide into more than four segments. The points P are the ends of nodal lines that extend along the body of the bell, dividing it into vibrating seg-

ments. Four is the smallest possible number of segments into which the bell can divide, and the tone proceeding from this mode of vibrating is its lowest possible note. A large bell, however, like a church bell, emits several other tones at the same time, usually including one from vibrating in eight segments, which is its highest note, and in a bell this is considered the "fundamental," and the one defining



VIBRATING BELL

The bell has lines of silence

the pitch, because it is the most prominent, immediately after striking. No bell is so perfect that these points of rest remain fixed. They are changed, too, by the stroke of the hammer, and when that is discontinued *they travel around the rim,* since the four vibrating segments are not strictly homogeneous. This accounts for the wavy ringing which the listener perceives as the sound of the bell grows fainter.

Vibrating strings produce little disturbance of the air and are therefore not very sonorous bodies. When used for musical purposes they are attached

to or supported on an elastic board or membrane. In some cases, like the violin and the guitar, this board is one side of a chamber of air which gives resonance to the vibrations of the string and board. We shall speak of resonance later.

The fundamental rate of vibration of a stretched string of circular cross section is found to depend upon the following four things, namely, the stretching force, the length, the density, and the radius. Considering only one of these quantities at a time as changeable—with a string of given length, density, and radius, the number of vibrations per second varies as the square root of the stretching force or the tension; whatever note the string emits with a given force it will vibrate twice as fast and produce the octave higher if the force be made four times as great, or an octave lower if it be only one-fourth as much. Keeping the same tension and kind of string, but changing only its length, the frequency varies inversely as the length; if a given length gives a certain numbers of vibrations, a string half as long will give twice that number, or twice as long, half as many, and so on. Also the number varies inversely as the radius and inversely as the square root of the density.

In rods vibrating transversely, the rate depends upon the mode of support as well as upon the form and material. Fixed at one end and struck or bowed at the other, or fixed at both ends and struck in the middle, a rod will produce both a fundamental and overtones. When free at both ends and supported symmetrically at two points about one-fifth of the length of the bar from each end, it will have nodes at these points. With a given length and thickness, the pitch of such a bar is the same for any

breadth; but with a given thickness, the pitch of one bar is an octave higher than of another if its length is $\sqrt{\frac{1}{2}}$ times as great. With the same length, its pitch is lowered an octave if its thickness is reduced one-half. The xylophone has thin bars of metal of different lengths, supported at their nodes, and struck with a wooden mallet. If the bar is bent the nodal points are nearer each other, passing through successive forms.

The tuning fork is regarded as a limiting case of a rod vibrating in this manner. Mounted on a board or box, its vibrations are communicated to the support by the vertical movement of the part between the nodal points.

A rod clamped at one end and stroked in the direction of its length with a piece of rosined chamois will vibrate longitudinally, its fundamental rate producing a wave such that the fixed end is a node, and the free end the nearest loop; i. e., the length of the rod is one-quarter of the wave length. A simple way to perform the experiment is to hold a metal rod three or four feet long and one-eighth to one-fourth of an inch in diameter between the thumb and finger of one hand and stroke it gently from the middle to the end. It will emit a clear, high, ringing tone. The ends being free to vibrate are at loops; the middle being held, the molecular motion there is impeded; the rod vibrates by its particles swinging from both ends toward the middle and again receding from it in both directions. The middle of the rod is therefore a node, and the length of the rod is one-half a wave length. A steel rod four feet in length would give a note of 2,000 vibrations per second.

CHAPTER XXVII

SYMPATHETIC VIBRATION—RESONANCE

A HEAVY weight suspended from a long cord, as a pendulum, will have a definite, unchanging period of oscillation. A slight twitch will move it very little, but if it is repeated at the end of the exact period of swing, the effect is increased, and with continued repetition the oscillation continues to grow until the weight is swinging in a large arc, simply from the superposition of small motions. A single individual may thrust his weight suddenly upon a bending plank, and by timing his efforts to fit the vibration period of the plank he may cause such a bending as ultimately to rupture it. It is the old story of requiring soldiers to break step in crossing a bridge that is of doubtful firmness. The one important condition is that the intermittent, small efforts shall occur at intervals that exactly coincide with the natural period of the body to which they are applied. When the primary agent, or the source of the first vibrations, is remote from the body upon which they act, the effect is called sympathetic vibration, and when rhythmic action in one body excites in another rhythmic action of the same period, the second body is said to be in resonance with the first. Although the source and the receiver of the disturbances are apparently disconnected, there is necessarily one medium through which the action is transmitted; both may rest upon the same table or

sounding board; or air may carry sound vibrations; or some medium throughout space as the ether may serve the same purpose. Such resonance is at the bottom of wireless telegraphy, both in transmitting and in receiving signals.

In the case of the pendulum, the vibrations would be augmented if the stimulus came only after every second or third swing, provided only that it coincided with those already set up, but the simplest effect is when the disturbing and disturbed actions are of the same periodicity. When a large body has thus been brought into vibration in its fundamental rate, it may take on subordinate vibrations, tremors of its own, differing in period from those exciting the resonance.

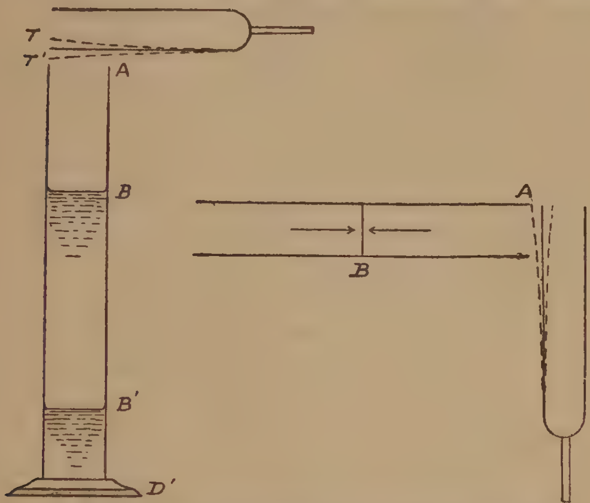
It is astonishing how small may be the effort required to affect the resounding body, and how prompt the latter is to respond. A plate of window glass coated with liquid was placed above a stove to dry; it became heated and somewhat strained; a toy music box, twenty feet away, was started playing, and upon the first tinkle from it the glass plate broke into fragments. By the merest chance the note hit the period of the plate which, already severely strained, needed only this vibratory addition to shatter it.

RESONANCE OF AN AIR COLUMN

In the case of sound the primary source of vibration may emit a tone which, in open air, is faint at a short distance away, but may set in vibration a body of air in an inclosed space that will produce a loud sound. Such a space is called a resonance chamber or resonator, and the air in it a resonance column.

Vibrations imposed upon a resonance column of air are necessarily limited in their progress in

nearly all directions by the walls of the chamber, from which waves are returned upon others that are advancing. Consequently the air assumes a segmental form with nodes and loops, and a determinate length of wave. This length, in turn, is controlled by the dimensions of the chamber. A given fixed chamber can resound, therefore, to certain



AIR COLUMN IN RESONANCE WITH A TUNING FORK

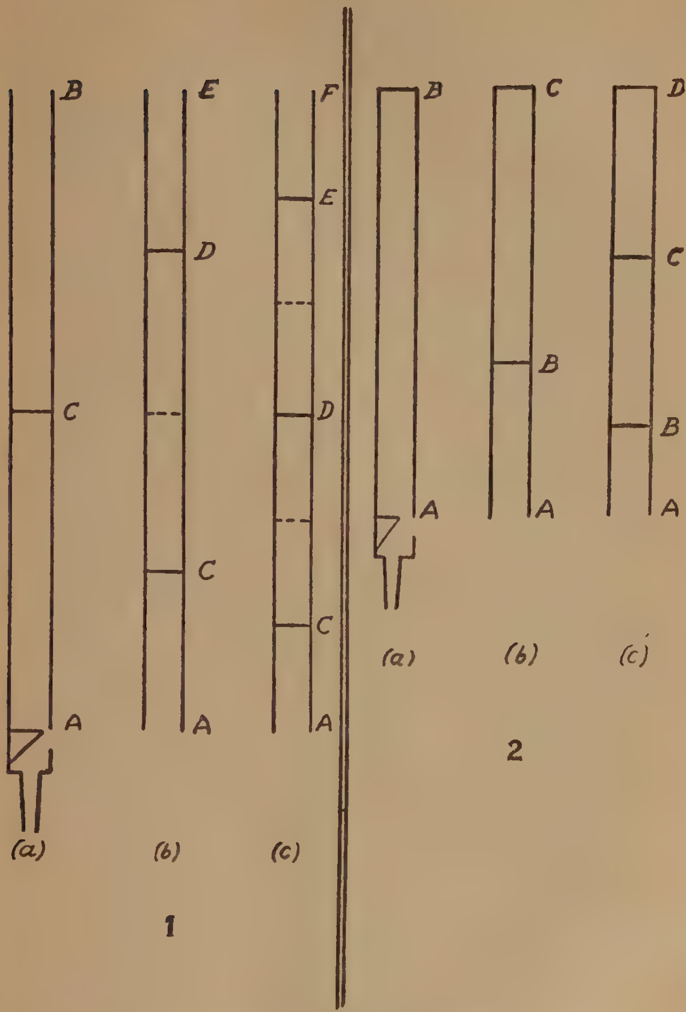
notes and not to others. One of the commonest illustrations is that of a column of air in resonance with a tuning fork. The vibrations of the column of air in this instance are precisely like those of the longitudinal vibration of rods. A vibrating tuning fork is held over a tall vessel AD, in which the length of air column may be varied by pouring in water, or, if more convenient, by a piston or plug moved from below.

A pulse, say of condensation, is started down the tube when the fork starts from T toward T′. If the

pulse travels down the tube and back to A by the time the fork has reached T′ and starts back toward T, the vibrating inclosed column will react upon the external air in the same way that the fork does, and will reenforce the sound. The same is true for the rarefactions, and the air column *resounds* to the fork. The first and most effective length of tube for this is when the condensation (or rarefaction) moves from A to B and back in a *single* swing of the prong, i. e., in one-half the period of the fork. Twice AB, then, is a half wave length, or AB is one-quarter of the wave length of the note produced by the fork. Four times AB, multiplied by the frequency of the fork, is the velocity of sound in the air in the tube.

If the water surface were at B′ instead of B, when AB′ is three times AB, the wave returning from B′ would synchronize with the fork, but it would be upon the *second* return from T′ to T instead of the first. The wave would have occupied three half periods instead of one to go from A to B′ and back. Then AB′ is three-fourths of a wave length. Resonance would occur if the air column were 5/4 or any odd number of quarter wave lengths, but it is strongest for the first. A like effect is produced if the fork is sounded before a tube open at both ends.

From this we are able to see how the air column in an organ pipe divides and produces its fundamental and its overtones. These pipes are either "open" or "stopped." In the former, Figure 1, (a), (b), (c), air blown across the edge of the mouth at A is agitated and sets up tremulous motion in the pipe, but is not blown through it. The dimensions of the pipe determine the vibratory movement of the air within it. Its fundamental note will result from the simplest order of vibration, which will be the node in



DIVISION OF AIR COLUMNS

1. In open pipes. 2. In stopped pipes

the middle and a loop at each end, as in (a). The pipe itself is then half as long as the wave, and the frequency of the note will be the velocity of sound divided by twice the length of the pipe. (In all these discussions we omit minor corrections on account of the width of pipe, curved extension of the wave at the open end, friction against the inside surface of the pipe, etc.) With a harder blast of air at A the air column may break into shorter segments, but as there must always be a loop at each end, and the distance from node to node must be twice as far as from node to either open end, the next division of the open pipe will be as in (b), where C and D are nodes, AC and DE are quarter waves, and half as long as CD. The pipe has four quarter wave lengths. The next possible division is as in (c), with six quarter waves. The lengths of the waves are the portions of the pipe length 2, 1, 2/3, etc.; the rates of vibration are as the reciprocals of the wave lengths, or as 1/2, 1, 3/2, etc., and these are in the same proportion as the successive numbers, 1, 2, 3, etc., or an open pipe is capable of producing the full series of overtones with its fundamental.

In the stopped pipe, Figure 2, (a), (b), (c), there must always be a node at the stopped end and a loop at the mouth, so the fundamental will correspond to a vibration of which the pipe is one-quarter of a wave length, as (a), the next three-quarters, as (b), the next five-quarters, (c), and so on. This means a frequency as the odd numbers 1, 3, 5, etc. While the first overtone of the open pipe is the octave of the fundamental, with the stopped pipe it is 3/2 above the octave. On the other hand, it is seen that the wave length, and consequently the pitch of a stopped pipe, is the same as that of an open pipe

twice as long; but while these two would have the same pitch, inasmuch as the open pipe usually has more overtones present than the stopped pipe, its note is the richer of the two.

A wind instrument of music without keys, such as the bugle or trumpet, is made to sound its several tones by changing the vibration of the lips. The player, however, can control this only far enough to produce a few notes, or divisions of the air column in the instrument. With the trombone, by sliding one part over another, the total length of air column in the pipe is lengthened or shortened, and consequently both the fundamental and secondary rates of vibration are altered as may be desired.

In a keyed instrument, as the cornet, with no key open, the instrument will give several notes as the trumpet does. In each such case there are nodal points where the air has little or no movement, but is alternately crowded upon or drawn away from them, and between which the movement is greatest. If the pipe is opened at a nodal point, the air there is at once free to yield to any compressing or rarefying, a node is impossible, the wave lengths in the pipe are altered, and the note is changed.

CHANGE OF TEMPERATURE PUTS AN INSTRUMENT OUT OF TUNE

The velocity of sound, and consequently the number of waves of any definite length per second, varies with the temperature. As the dimensions of the organ pipes are very slightly affected by temperature, although the wave length is materially altered, the pitch of the notes from the organ will be different with varying temperature. Not only so, but inasmuch as the length of wave from a given pipe de-

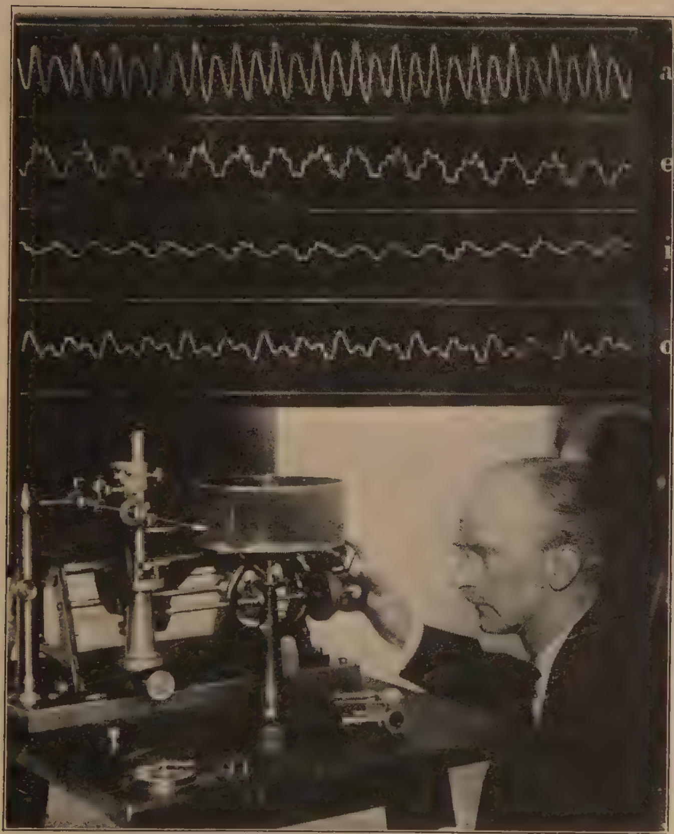
pends somewhat on the width of the pipe as well as its length, the change will be different in different pipes, so that if they are tuned to correct pitch for one temperature, the instrument may be out of tune at a different temperature.

There is a pitch of voice to which any room or hall readily responds. A speaker adopting this as the dominant pitch in speaking feels his voice sustained by the resonance, and an experienced orator soon discovers the pitch appropriate to the hall in which he speaks.

A very slight change in the size or shape of a cavity will alter its responsiveness to sound, and make it resonant to sounds of different pitch. It is this that provides the modulation of the voice, for perhaps the most remarkable resonance chamber is that formed by the mouth, throat, and nasal passages. Its wonderful adaptability meets all the inflections of the voice in speaking and singing, and reveals unsuspected variety in vibration that could not be easily detected by any other means. A striking example is in the crude instrument called the jew's-harp. This has a single reed or tongue vibrating between the teeth, with the mouth cavity back of it to reenforce its vibrations. Without this it is scarcely audible; yet with it, the instrument exhibits a considerable range and complexity of vibration, brought out by very slight change in the positions of the tongue, lips, or cheeks.

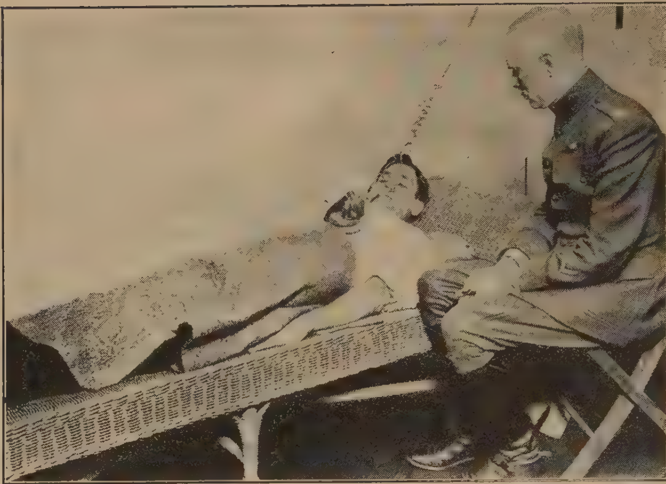
QUALITY OF SOUND

Besides the pitch and the intensity of sound, a third characteristic is more diverse, more pervading, and more variable in its effects than either of those. This is termed the *quality* of the sound. It is the



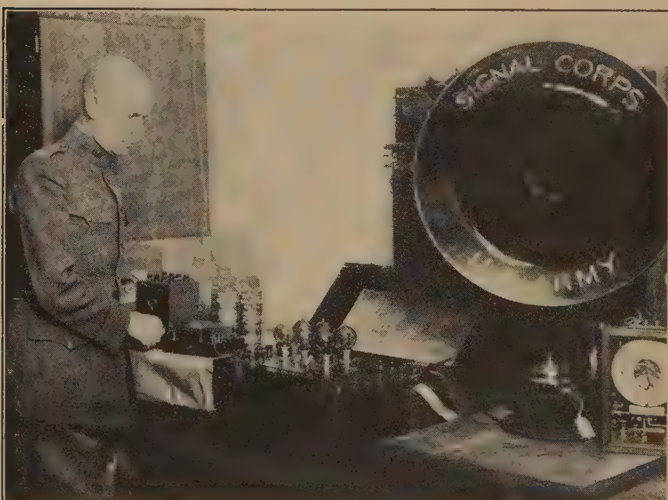
CHARTING SOUND

The device is intended for studying and improving phonograph records. As music is heard on the phonograph, the needle in the foreground records the vibrations on the circular strip.



Copyright, Keystone View Co.

A SOUND AMPLIFIER AND A STETHOSCOPE RENDER THE PATIENT'S HEARTBEATS AUDIBLE A MILE AWAY



Copyright, Keystone View Co.

AMPLIFYING HORN, WHICH MAGNIFIES THE SOUND OF A DISTANT PATIENT'S HEARTBEATS FOR DIAGNOSIS

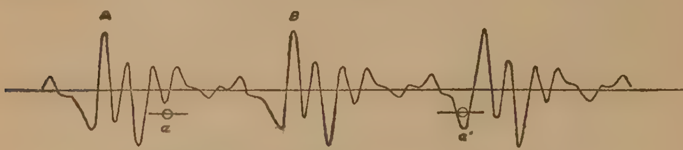
peculiarity by which we distinguish between two sources that are producing the same fundamental tone. Of two voices singing the same note, equally loud, one may be clear, flutelike, and simple; the other rich, full, sympathetic, laden with tones that give the note a very different character; we at once recognize two different voices. When a note is played by two different instruments invisible to us, we have no difficulty in recognizing the violin and the flute, and in distinguishing between them, although the vibrations excited by the two sources are transmitted to the hearer and communicated to the ear by the same medium, the air.

The quality of a sound has been found to be due to the *overtones*, any of which may be present with the fundamental, and in any degree of relative intensity.

Special resonators can be constructed for any pitch, and a cylindrical form, with one part sliding over the other like a telescope, can be adjusted to resound to tones of different frequencies. With such resonators Helmholtz and Koenig not only succeeded in resolving complex sounds into their constituent elements, picking out the different partials by different resonators, but by sounding forks of the predetermined rates of vibration before their appropriate resonators, they *reproduced* the original sounds with remarkable fidelity.

The quality of sound, however, is affected by variations too slight to be readily thus reconstructed, or synthesized, since intensity as well as frequency or pitch has to be observed. In acoustic analysis today it is more common to obtain a photographic record of the complex vibration, and resolve that into its component partials. The tracing point of a

phonograph disk actuates a sensitive lever to which is affixed a small mirror. From this a beam of light is focused upon a sensitive film, and produces a tracing of the most complex vibration, as the film is moved rapidly along. The figure on this page is an enlarged view of such a record made by the vowel *a* in *father*. The distance from *a* to *a′* on the tracing represents 1/100 of a second, and contains about one



PHOTOGRAPHIC RECORD OF A VOWEL SOUND

and a half fundamental waves; the pitch of the voice, therefore, was about 150 vibrations per second.

Various mechanical contrivances have been devised, ingenious but intricate, to which a tracing pencil is so connected that on moving it along the vibration record repeatedly, with setting to correspond to the various wave lengths, the constituent curves can be made out separately. In the above figure there are at least eight such elements, indicated by the peaks in one large wave, as from A to B.

A series of pipes constructed to produce these separate notes, and sounded together, will reproduce the vowel sound "a" with the same quality.

In some musical instruments the air is put into vibration by a slender thin blade of wood or metal in the mouthpiece. This has its own rate of vibration, when blown upon, and gives the pitch of the fundamental for the pipe with which it is connected. The clarinet is an instrument of this type. Besides the style of organ pipe already mentioned, or "flue"

pipe, an organ sometimes has sets of these "reed" pipes which have a different quality of tone from the flue pipes. Air is blown through the opening over which the reed fits, and the latter opens and closes the orifice as the reed vibrates. This is a "striking" reed. In another form the reed vibrates into and out of a passageway.

This passage opens into a large air chest or resonance chamber, in common with other reeds, as in the "cabinet" or parlor organ. In the common harmonica, played by the mouth directly, the reeds are of this kind.

CHAPTER XXVIII

DIFFRACTION AND REFLECTION OF SOUND WAVES

IN the passage of sound through a slit or an orifice, if the wave is very short, or the opening is large compared to the wave length, the disturbance passes through with little change, and the space on every side behind the surface thus penetrated is in shadow; but if the wave is long, or the opening is relatively small the effect spreads around the edge and behind the obstacle. It is because usually sound waves are long, perhaps seven or eight feet, or more, that sound is not more completely cut off by intervening objects, or sound shadows are not sharp. It is strikingly different with the sound of a railroad train after the train enters a tunnel, or before it emerges from it. The mouth of the tunnel is large and the sound waves continue in the direction of the tunnel line, but are effectually cut off to either side. When the train comes out it is heard loudly and suddenly. With very high notes, of wave lengths less than an inch, clear, definite, sound shadows can be observed from openings less than an inch in width.

REFLECTION OF SOUND WAVES

The direction in which waves are progressing may be changed by reflection from a body into which the wave disturbance does not penetrate; by refraction in passing through a body; and by diffraction in

passing the edge of an obstacle, or through an orifice. The spherical shell of air comprising a single sound wave has been successfully photographed by Professors Arthur L. Foley and Wilmer H. Souder, of the University of Indiana, the photographs showing the form and position of the wave at different times, and after undergoing changes of form by reflection from various surfaces. The perviousness of such a shell to light is not the same as that of the undisturbed air, from which it differs in density, and in its condensed and rarefied portions it casts a ring of shadow with an adjacent one of light.

The sound was produced by a short electric spark between two knobs inclosed within a long, light-proof box. A more intense flash, timed to follow closely upon that producing the sound, cast a shadow of the wave upon a sensitive photographic plate at the other end of the box. The wave length was very small, and the shell, therefore, exceedingly thin, appearing in the photograph as a mere line. Numerous photographs by these physicists show that sound waves undergo all the modifications that theory and experiment indicate for waves in general.

ECHOES

The most familiar example of a reflected sound wave is the echo. A wave is reflected from a surface at an angle equal to that at which it impinges upon it, and a sound may be reflected from the faces of cliffs, hillsides, walls, or other surfaces, and be returned distinctly to a listener, especially if he is in an elevated position. Reflected from a curved surface the waves may converge upon a focus, and the sound be especially strong and distinct there while not perceived elsewhere. Within doors, this effect is

produced by the walls of a large room, and from the surfaces or arches and domes. Sometimes by reflection from various surfaces a number of echoes of the same original sound are heard. A roll of thunder may follow a single flash of lightning, the initial crash reverberating in echoes by reflection from clouds at various distances.

With sound traveling 1,100 feet per second, if a speaker uttered five syllables in a second, these might all be heard distinctly when reflected from one surface at a distance just exceeding 550 feet, for they would all be uttered before the echo of the first would reach the speaker, and there would be no confusion; but a single syllable may be heard in echo several times by reflection from different surfaces at various distances. Some regions are famous for the number of times a single sound is thus returned, as many as fifteen or twenty such repetitions having been observed.

An interval of one-tenth of a second between two words or syllables is long enough for most people to recognize them separately. If the reflection of one syllable from a distant surface does not return to the speaker or a hearer within that time, or by the time the next syllable is uttered, it is not likely to make confusion with it. In one-tenth of a second sound will travel 110 or 112 feet, and in an auditorium sixty feet long words from a speaker at the front will at once reach a hearer ten feet away directly, and again, one-tenth of a second later, by reflection from the rear wall. The reflected sounds would probably produce confusion but for their diminished intensity.

When the sounds are reflected from curved surfaces they may be more intense at certain points

than the direct sounds. Waves issuing from one focus of an ellipse are concentrated again in the other focus. In a room with walls or roof of this form, a slight sound at either of these points is easily heard at the other, though not loud enough to be heard elsewhere. Such conjugate points are to be found in various buildings, the rooms being known as whispering galleries.

The acoustic qualities of an auditorium depend upon so many things, and are influenced by causes so slight, that it is not possible to know in advance whether a hall built upon a given plan will be a success or a failure in this respect. Much study and experimenting have been expended in investigating the subject, but only a few very general canons can be depended upon. Since regular reflection occurs only from smooth surfaces, paneling the walls prevents such reflection, and since focusing of the waves results only from reflection from curved walls or ceilings, the shape, position and dimensions of these should be considered. In domes and ceilings, some treatment of the surfaces that will break up their smoothness is useful.

The most effective means yet known to remedy the bad acoustics arising from echoes and reverberations, is to hang upon the walls drapery that will absorb the waves instead of reflecting them.

When sound is produced in the open, the energy of vibration is expended upon the air on all sides, but if the waves are formed at the larger end of a funnel or horn, they are confined, and at the smaller end of the air column may even be intensified. The horn is a resonator. In this manner the ear trumpet aids in hearing; and the speaking trumpet or

magaphone, while restricting the sound to one direction, makes the voice stentorian.

If, when the sound is produced at the larger end of the horn, the smaller end is closed by a thin elastic diaphragm of metal or parchment, or other membrane, this vibrates in every degree of complexity under the waves concentrated upon it. A stylus fastened upon the vibrating disk will make a path in soft plastic material which is moved along beneath it. A hard metal copy of this tracing is made by electrotyping, and with this, by pressure, copies are made in hard rubber, which has been temporarily softened for the purpose by heating. Of course the actual making of a phonographic record requires many refinements of work beyond this outline, but the result is a wonderfully faithful mechanical reproduction of sound waves. In the earliest instruments, the record consisted of indentations in a sheet of tin foil by the vibrating point. The point was then made to go over the same tracing and the sound might be reproduced by the same disk that made it in the first place. In a later chapter we shall see that the telephone is no less remarkable in reproducing the original vibrations magnetically.

The disk may be made to vibrate by various means. In the horn of the automobile the thrust of a rod by the hand moves the rim of a wheel which drives another at a higher speed. The latter has a larger toothed rim, which presses against the end of a rod. This is riveted at the other end to the metal disk at the small end of the horn. The strokes of the teeth against the rod makes the disk vibrate, and this produces the "horrible honk" of the automobile. In an improved form the toothed wheel is on the

shaft of a small motor driven by the electric current from a storage battery when the autoist closes the circuit. The sound of the horn may thus be sustained as long as the current is kept on, instead of being a single croak. The disk is strong and the note is coarse and rough, with a pitch of one hundred to two hundred vibrations per second.

CHAPTER XXIX

MAGNETISM

A SPECIES of iron ore found centuries ago in the province of Magnesia, in Asia Minor, and subsequently in many parts of the world, is called magnetite, and possesses some peculiar properties known as magnetism. A body in its native state, like this ore, which possesses these properties is a "natural" magnet or lodestone; other bodies can have magnetic quality imparted to them, and they are then "artificial" magnets. Substances which can be converted into magnets are magnetic substances, and the process of so converting them is magnetizing them or magnetization. The characteristic properties of a magnet are:

1. It will attract iron and a few other substances that are magnetic, but much less so than iron.

2. It will attract or repel another magnet.

3. It has at least two portions at opposite ends or sides, both of which will attract bits of iron, but the portions between them will not do so.

These two parts are called "poles" of the magnet. When the body is dressed into prismatic form, with the poles at the ends, it becomes a bar magnet. The line joining the poles is the axis of the magnet.

4. If a bar magnet be suspended or pivoted at its center, so as to move freely in a horizontal plane, it will place itself with its axis in almost a north and south direction, and, however it is displaced, when

left free it again assumes this position, with each pole pointed in the same direction as before.

This property makes it available as a guide, and gave the ore the name lodestone, meaning a leading or guiding stone.

5. A piece of iron in contact with the lodestone or stroked by it acquires temporarily these same properties, but loses them when it is removed from

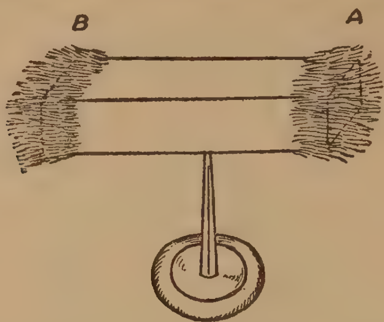
MAGNETIC IRON ORE WITH CLUSTERS OF IRON FILINGS CLINGING TO ITS POLES

the magnetizing body; it is a temporary magnet. A piece of steel thus magnetized, retains its magnetism and is a permanent magnet.

6. A magnetic body placed in proximity to a magnet is in some way influenced by it so as to be magnetized without touching it. Iron may thus be strongly magnetized, but loses its magnetism when the magnet is removed. When thus influenced the iron is said to be magnetized by induction.

7. An artificial magnet, whether produced by contact or induction, exhibits all the characteristic properties of a natural magnet. If it is a slender rod of steel, and suspended or supported on a pivot so as to turn freely, it is called a magnetic needle, the poles being virtually at the ends.

8. If a magnetic needle is suspended at its middle it settles to rest, pointing approximately north and south. The end pointing northward is usually termed the north pole, and the other the south pole of the



MAGNET WITH IRON FILINGS CLINGING TO ITS POLES

needle—sometimes the "north-seeking" or "south-seeking" pole, but always the north-seeking is designated positive or +, and the other negative or —. If the positive pole of a magnet is presented to the like pole of a needle, it repels it; if to the other pole, it attracts it, and, in general, like magnetic poles repel one another, unlike attract.

MAGNETISM BEGINS WITH THE MOLECULE

Suppose a magnetic needle to be delicately poised, and a long, slender one, like a knitting needle, to be tested as to its polarity by the preceding method. One end repels the north pole of the needle and attracts the south pole; the other end attracts the north and repels the south pole; at the middle point both the north and the south pole of the needle are attracted. Let the long bar be broken into halves; each half will be found to be a magnet like

the original rod, with positive and negative poles and a neutral point midway between. If each of these be again broken into halves, all four pieces will be complete magnets with two poles, and the like holds true to the smallest division that can be effected. The indication of this is that the magnetization is ultimately in the molecules of the substance. It is supposed that in magnetic substances, every molecule is a magnet with its north and south poles. When the substance is not magnetized the molecules occupy miscellaneous positions that are stable, but when brought under magnetizing influence, they are made to readjust their positions so as to place their axes parallel, with their poles directed alike. This results in neutralizing the magnetic action of a magnet except at or near the ends. This process is magnetization, and is slight or considerable according to the degree to which the molecular magnets are brought into parallelism. The molecules of iron yield readily to such an influence, but resume their original position when the disturbing cause is removed; in steel they are harder to disturb in the first place, but when brought into parallelism they retain that position.

Since either pole will attract a magnetic substance it is seen that the test of polarity is not attraction but repulsion.

INCLINATION OF THE NEEDLE

A steel needle accurately balanced about an axis, will not be so balanced after it is magnetized. In the greater part of the northern hemisphere the + or north-seeking pole will dip downward or incline toward a point within the earth somewhere in the vicinity of the north pole. The angle it makes with

the horizontal is called the "dip" or "inclination." It increases in going from the equator northward until (in 1900) at a point in Lat. 70° 5′ N. and Long. 96° 43′ W. the dip was 90° or the + pole was directed vertically downward. Going southward, the — pole is depressed, and (in 1909) in Lat. 72° 25′ S. and Long. 155° 16′ E. the needle stood vertically, with the — pole directed downward. These two points are termed the magnetic poles of the earth, and the needle usually points to them instead of the geographic poles, and a circle of the earth through a given place and the magnetic pole is a magnetic meridian of that place.

A magnetic needle counterbalanced to neutralize the dip becomes a "compass" needle, and swings horizontally. A line may be traced upon the earth from the north magnetic to the south geographic pole, and from the south magnetic to the north geographic pole, at every point of which the needle will point to the true (geographic) north or south. On a line from the north magnetic to the north geographic pole, the north pole of the needle will point toward the magnetic pole and southward or *directly away* from the geographic pole, and similarly with the south pole of the needle between the southern magnetic and geographic poles. The two portions of the lines on which the needle points north and south are usually marked "agonic" on a magnetic map, and also the "magnetic equator" is shown, which is a line through the points where the dip is zero. The agonic lines are not symmetrically situated on the earth. In America, at any point east of the agonic, the needle points west of true north, and at a point west of the line the needle points east of north.

DECLINATION OF THE NEEDLE

The angle which the needle makes with the true geographic meridian is called the magnetic declination, or deviation of the needle. On the agonic line the declination is zero. The declination at any point is not constant, but is subject to several systematic or cyclic changes. At New York, in 1908, the declination was 10° 14′ W. and the inclination was 72° 13′ N. The variation in declination is often spoken of loosely as "variation of the needle."

CHAPTER XXX

THE EARTH'S MAGNETIC ACTION

BESIDES the inclination and declination of the needle there is a third element necessary to determine completely the earth's magnetic action. That is the intensity, meaning the actual force in mechanical units, with which a magnetic pole is urged. It is the resultant of the force tending to move the pole horizontally north or south, and that impelling it vertically downward. This, like the other elements, varies with the locality. In scientific nomenclature it is always expressed in dynes per unit strength of pole.

The force acting on the north-seeking pole tends to draw the magnet toward the north, and that on the other pole to the south, but the magnet as a whole is not drawn in either direction. A needle resting upon a cork floating in water merely assumes a definite direction without moving to the north or south; the action upon the two poles is equal and oppositely directed. This directive action is systematic, as if the earth, or a core within it like the core of an apple, were itself a huge magnet, with its poles hundreds of miles beneath the earth's surface. But the action is too variable in its distribution and too irregular to be explained on any simple hypothesis, and these so-called magnetic constants have to be determined for various places by direct experiment or official surveys.

The most satisfactory way to compare one magnetic pole with another is to measure the force with which they attract or repel each other at a given distance apart. Careful measurements show that the force between two magnetic poles is directly proportional to the product of the pole strengths and inversely proportional to the square of the distance between them. The next step is to decide how strong a pole we shall regard as the unit by which to measure "pole strength," and in all scientific usage a pole of unit strength is a pole that will repel an equal pole of the same kind at a distance of one centimeter with a force of one dyne. Then, always, the force in dynes between any two magnetic poles is the product of their strengths divided by the square of the distance (in centimeters) between them. We can now understand the exact meaning of the intensity of the earth's magnetism, spoken of above: it is the number of dynes, attractive or repellent, upon a unit pole. At New York it is just about six-tenths of a dyne, directed at an angle of 72° 2′ from the horizontal. The vertical component is .532 dyne, and the horizontal, .1867 dyne.

COMPARISON OF MAGNETIC AND GRAVITATIONAL FORCE

By comparing this measure of magnetic force with that of gravity we find that for two bodies to attract each other by gravitation with so small a force as one dyne, at a distance of one centimeter, the mass of each would have to be 8.5 pounds, or if one of them was the unit one pound, the other would have to be seventy-three pounds. The force of one unit magnet upon another unit at a distance of one foot is seventy-three times as great as the attraction of

one pound of matter upon another pound at one foot distance.

The unit strength of pole is very small, the total pull of the earth upon it at New York being about $\frac{1}{50,000}$ of a pound, apparently an insignificant force, but the pole of a small toy magnet may have as many as a hundred units of strength, and with large commercial magnets it is many thousands of times as much as this, and the pull of the earth upon them is greater in the same proportion.

A line joining the magnetic poles of the earth is its magnetic axis. This is not constant in position, but describes a slow rotation about the geographic polar axis, and the three elements, declination, inclination, and intensity, undergo gradual change.

In a bar magnet the poles are practically at the ends of the bar, and therefore, as far apart as the size of the bar will permit. In this form either pole can be used independently of the other. When the whole lifting force of the magnet is to be used, it is more effective to bring both poles into action, and for that purpose the iron or steel is in the shape of a horseshoe. A small bar of iron across the poles of such a permanent magnet, called its armature, neutralizes its external effect, and in some measure prevents the steel from losing its magnetism.

Other considerations that make this form desirable will appear under "Electricity."

FIELDS OF FORCE; LINES OF FORCE

The action of a magnet extends through the medium surrounding it, such as air or water, and is also transmitted through a vacuum. No objects except magnetic substances intercept such external action. There are, however, only a few substances

that are susceptible to it. These are most notably soft iron and steel; then, less strongly, nickel, cobalt, and possibly, in a scarcely perceptible degree, a few rare metals.

Whatever may be the ultimate nature of magnetism, we can visualize its action in the medium around it. In the first place, the effect of either pole at any point is determined by the force it would exert there upon a unit positive magnetic pole. The entire region in which such force is manifested is called a magnetic "field of force." The number of dynes with which the unit pole is urged, at any point in the field, is called the "strength of field" or "intensity" at that point, and the path along which the pole, if it could be tested by itself, would move, is evidently in the direction of the force itself, and is called a "line of force." The field of force may be due not merely to a single pole of one magnet, but to both poles and to any and all magnets whose influence extends to the region under consideration.

A small magnet turning freely on a pivot, at any point in the field, would take a position showing the direction of the line of force, for the + pole is drawn along the line in one direction and the — pole in the opposite direction. Accordingly, if a magnet be laid upon (or under) a piece of paper, and fine iron filings be scattered over the paper, each minute particle is magnetized by induction, one end is + and the other —, and they connect up along lines of force.

If a free positive pole were placed at a point on one of these lines, it would be attracted by the south pole of a magnet and repelled by the north pole, and would move to the former, but it would not go in a straight line; it would follow the curved path

of the line on which it was situated, for that line shows the direction of the force at every point of the line. For more exact purposes, Faraday introduced the further idea of supposing a single line of force to be represented by an elastic string, in such tension as to pull with a force of one dyne. This would be a unit line of force. Such lines are supposed to be so distributed throughout the field as to indicate the strength of field. In a uniform field they are distributed uniformly, and in a field of varying strength they are gathered closely at some places and sparsely at others, the strength of field being represented by the number of lines per square centimeter of area perpendicular to the lines. In a uniform field of unit strength, there is one line per square centimeter of area; in a uniform field of ten units strength there are ten of these dyne lines penetrating every square centimeter. In the earth's magnetic field, at New York, where the intensity is 0.6 dyne, the lines are parallel, pointing in the direction of the north magnetic pole, inclined at 72° .02′ to the horizontal (for that is the direction in which a + pole would be impelled to move), and there is one line to every 1.67 square centimeters of area of a plane perpendicular to the lines.

This mental picture leaves vacant spaces between the lines, but there is no such place where the magnetic force is not felt. So the idea has been modified to fill up the field by assuming that the magnetism acts along "tubes" of force, a tube taking the place of a line, and having an area of cross section equal to the area apportioned to one line. It must be kept in mind that the whole conception of lines and tubes of force is only a method of making magnetic conditions vivid.

A piece of iron or steel in a magnetic field becomes a magnet by induction. The entire earth is surrounded by a magnetic field of varying intensity, and any piece of iron left undisturbed for a little while acquires a polarity, the north pole below and the south above. If it is a rod in an upright position this difference of poles is readily shown by bringing up to it a sensitive magnetic needle; the north pole of the needle is repelled by the lower end of the rod and attracted by the upper. All iron uprights—columns, posts, even stoves that have been for some time unused—are thus magnetic in character. We live in a magnetic field and are always in the presence of magnetized bodies. The magnetization of a bar by induction is aided by striking the bar sharply with a hammer, as that apparently jostles the molecules and permits them more readily to take a position with their magnetic axes parallel to the lines of force. The more completely this molecular arrangement is effected, the more strongly the bar is magnetized. If it is reversed in position its polarity is reversed; the north pole always being pointed in the direction in which a free magnetic + pole would move. A magnet is demagnetized by a temperature of a dull-red heat or higher.

In the mariner's compass, the needle, delicately pivoted, and carrying a cardboard dial that is marked with the cardinal points N. E. S. W. and intermediate angular directions, is in a frame that is swung on gimbals so as to be always horizontal, no matter how the base on which it stands may change its position with the movement of the ship. Steadily pointing in a constant direction, it has been the navigator's guide and chief reliance for centuries.

When the hulls of ships came to be made of iron, the violent riveting together of the plates magnetized them—the hull itself acquires a magnetized condition that it retains in some measure when its position is altered. As a consequence, on such a ship the compass would be quite untrustworthy if it were not "compensated" by magnets so disposed about it as exactly to counteract the effect of the ship's magnetism. Even so, it is necessary from time to time to "swing the ship," i. e., to move it around a circle

A MARINER'S COMPASS

at sea, with some distant fixed object in sight, to test whether the compass needs readjustment.

The failure of the magnetic compass is still more complete in a submarine vessel where it is completely insheathed within iron walls, the deck of the ship as well as the hull. Here, and to a considerable extent on other vessels, especially ships of war, the old-fashioned mariner's compass is giving place to the "gyrocompass." The explanation of the gyroscope belongs to rather advanced mechanics, but fundamentally its action rests upon the persistence of a rotating body in its plane of rotation. If a heavy disk or a thin disk with a heavy rim rotates very rapidly, it will require a considerable force to turn its plane into a different position. If it is mounted upon a pillar that turns freely about a

vertical axis, the gyroscopic disk will maintain its plane of rotation without change no matter in which way or how far its supporting column is turned.

Such a disk, of bronze or other nonmagnetic material, properly placed upon a ship and driven mechanically at a very high speed (approximately 150 revolutions per second), continues to rotate in the same position no matter how the ship turns. Thus it is as good an indicator of direction as the magnetic needle, while itself free from magnetic influences. Even a slight pull upon it, however, if long continued, will affect it somewhat, and this effect from the rotation of the earth is avoided by having the axis of the disk parallel to that of the earth; its rotation, then, coincides in direction with that of the earth itself, and is not disturbed by it.

VARIOUS USES OF MAGNETS

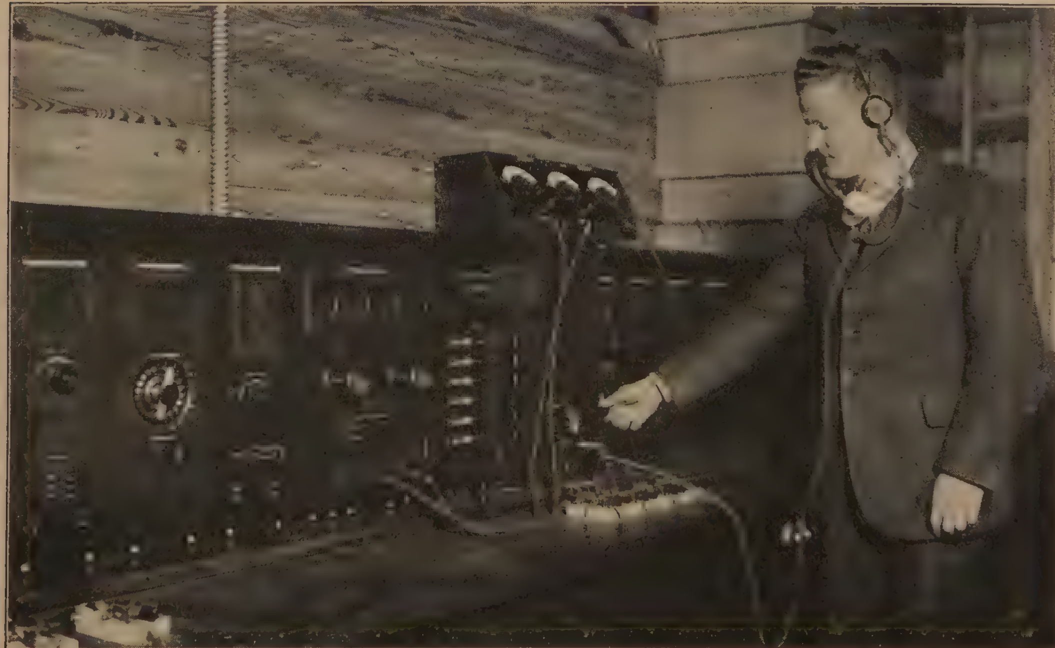
Magnets are used in innumerable ways, especially in commercial and industrial applications. They lie at the base of all telegraphic and telephonic communication, and are the chief feature in all electric motors and dynamos, and consequently in all electric power and lighting; but in nearly every application of this kind the magnetic field and the magnet are produced by means of electric currents.

CHAPTER XXXI

ELECTRICITY—ATTRACTION AND REPULSION

IN electricity, as in magnetism, the fundamental phenomena are attraction and repulsion, but while only a few substances can be magnetized, all bodies can be electrified. There are many features of resemblance in both, and there is unmistakably a very close connection between them, but there are also differences and distinctions so sharp that one should not be confounded with the other.

Electrification is a condition into which a body may be brought, and which it may lose, and for a while it was supposed to be confined to the surface of the body. When in this condition the body attracts other objects, and if these are light and dry like little pieces of paper, or feathers, they cling to it in clumps much like the iron filings clustering about the poles of a magnet. In the earliest experiences, this property was most strikingly exhibited by the resin amber, for which the Greek name is *elektron,* and from that the word "Electricity" was made, to indicate a "something" which the body might have communicated to it, or with which it might be said to be charged. It was soon found, however, that the same peculiarities were displayed by many other substances, and in varying degrees. Not only so, but there were distinct similarities and contrasts in the charges of electricity, very much like those noted



Photo, Paul Thompson

CONTROL ROOM OF THE "LOUD SPEAKER" THAT REPORTED MR. HARDING'S INAUGURAL ADDRESS

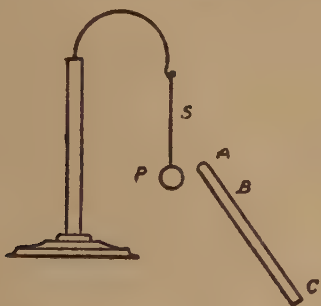
Copyright, Ewing Galloway

THE TRANSMITTER BY MEANS OF WHICH A TRANS-ATLANTIC LINER TALKS WITH STATIONS ON SHORE

in magnetism; there seemed to be two kinds of electricity of opposite character—at all events there were two opposite kinds of electrification.

Among solids, hard glass, sulphur, resins (and, in later times, hard rubber) were particularly excitable, and so were silk, wool, and fur; metals also could be electrified, but they would immediately lose their charge unless certain precautions were observed.

The means of electrifying a body was simply friction—rubbing it with some other material, but when so electrified a body would communicate its charge or a part of it to another body by mere contact with



ELECTRIC ATTRACTION AND REPULSION

The ball of pith, *P*, is first attracted and then repelled by the part of the rod, *A B C*, that has been electrified by friction

it. In the figure, P is a small, dry ball of pith, suspended by a silk thread S, and preferably covered with thin metallic foil as gold leaf. It is very light. ABC is a rod of sealing wax. The end C may be held in the hand, and if the portion AB is rubbed with a flannel cloth and then presented to P, it will attract the ball even from a distance of several inches. P adheres to A for a few moments and then springs

away, and no coaxing on the part of A will induce it to return—violent repulsion has taken the place of attraction.

Instead of sealing wax a rod of glass might have been used, and while friction with flannel might not have produced any very marked effect, if the glass rod were rubbed with silk it would cause the ball P to act just as in the case of the sealing wax. But now a remarkable difference comes to light. If there are two such balls P in independent suspensions, one charged by the sealing wax and thereafter repelled by it, and the other charged by the glass and thereafter repelled by it, the former will be attracted by the glass, and the latter will be attracted by the wax.

From this and many other evidences it appears that there are two opposite kinds of electrification, or electrical charges, one like that of a glass rod rubbed with silk; the other like that of sealing wax rubbed with wool. The former is positive (sometimes called "vitreous") and the other negative (sometimes called "resinous"). These same experiments bring out still another important fact. When one body is electrified by friction with another, the second body is electrified equally with the first, but oppositely in kind.

It seems, then, that the production of a charge of one kind of electricity is attended by the production of a charge of the opposite kind at the same time.

Bodies similarly electrified, positively or negatively, repel one another; and those oppositely electrified attract one another.

CONDUCTORS AND NONCONDUCTORS

In the figure just described, P was attracted and then repelled by the portion AB of the rod. The part

near to C would have no effect, and the like would be true of the glass rod, showing that the charge of electricity in these cases is confined to the portion of the rod that is subjected to friction. It would not have been so with a metal rod. Indeed, held in the hand, the rod of metal would show no sign of electrification, but if it were held in silk, or by a glass handle, it could be charged by rubbing it with either silk or wool. The charge would be found, however, to be distributed over the whole rod, no matter which part had been rubbed. A body on which a charge thus distributes itself is called a "conductor" of electricity; one on which a charge remains located on one portion of it is a "nonconductor." Bodies are of every degree from very bad to very good conductors, probably none being perfect in either respect. In general, metals are good conductors; organic substances such as wood, paper, gums and resins, silk, wool, also glass, sulphur and rubber, are poor conductors; gases are the poorest, and a perfect vacuum is probably perfectly nonconducting.

Dry air conducts very imperfectly, but a charged body rapidly loses its charge or is "discharged" when surrounded by moist air. An envelope of nonconducting material prevents the escape of an electric charge through it, and is called an "insulator." Because metals and the human body are conductors, it was necessary for the metal rod to have an insulating handle, to charge it successfully; and for a like reason the charged pith ball had to be suspended by a silk thread. Metal objects are usually mounted on glass or rubber stands, or are suspended by silk cords, if they are to hold an electric charge. Electricity on insulated bodies is called "static" electricity, and the science dealing with it, *Electrostatics*.

ELECTRIFYING BY OTHER MEANS THAN FRICTION; INDUCTION

Electrification may be produced by other means besides friction. Sudden cleavage of crystalline substances will leave the two portions electrified oppositely, as will also the tearing of a piece of paper; friction between any two dry bodies will accomplish the same result, even if they are not of different material; in short, any action that excites the surface molecules of a body is likely to electrify it, though this effect is not always easily detected. But the most common method of charging a body is by induction.

If a body that is charged, say negatively, is brought near an uncharged one that is insulated, a positive charge is induced upon the latter on the side nearest the negative body, and a positive charge is repelled upon the insulated body to its extreme limit. On touching the body, this free charge is further repelled—perhaps to the other side of the earth, and on breaking contact with it, and removing the first or inducing body, the charge of positive electricity that was bound by it spreads over the whole surface, and the insulated body is charged positively by induction.

MEASUREMENT OF ELECTRIC QUANTITY

Since any electrified conductor will share its charge with an unelectrified one, it is plain that the charge on either may be increased or decreased, and to compare charges accurately it becomes necessary to have some unit by which to measure them. Accordingly a unit has been adopted to measure the quantity of electricity with which a body is charged,

and another to measure the degree to which it has been electrified. This is very like the procedure with heat where one unit is employed to measure the quantity of heat applied to or removed from a body, and another to determine the difference of temperature in the body.

If bodies are very small they may be treated as concentrated at their centers, and if one that is charged is put in contact with an uncharged one of the same size, the quantity on each becomes one-half as great, and this can be further subdivided as we please.

Now, any two such bodies, at a fixed distance apart, say one centimeter, are found to repel each other with a force that is proportional to the product of their charges; and with a fixed charge on each, the force of repulsion decreases as the square of the distance increases; or, the force is directly proportional to the product of the quantities, and inversely proportional to the square of the distance between them. Everywhere, now, the unit quantity is taken to be the quantity which will repel an equal quantity of the same kind, at the distance of one centimeter, in air, with a force of one dyne; and always in c. g. s. units the force is the product of the quantities divided by the square of the distance between them.

The attraction or repulsion from an electrified body extends indefinitely into the surrounding space, but decreases in intensity with the square of the distance. It thus constitutes an electric field of force that may be depicted by lines of force like a magnetic field, with this difference—magnetic lines of force from a north pole of a magnet join with the south pole either of the same or of another magnet; electric lines of force from a positive charge on an insulated

body connect with some other body. A body may have either kind of electric charge separately, but a magnet always has both poles on the same piece of metal.

THE CONNECTION BETWEEN ELECTRIC CHARGE AND ENERGY

If an insulated conductor is charged, say positively, and then put into metallic connection with a similar insulated uncharged body, it will divide its charge with this, and a portion of the positive charge is said to have passed from the first body to the second. If the positively charged body had been thus connected with one like it charged equally negatively, they would both have been discharged, as if the charge on the first body had flowed along the wire to the second body and neutralized the negative charge there. Now whether or not there is such a thing as positive or negative electricity to be thus transferred, there is undoubtedly a transfer of electrification; in either case such a transference is "an electric current." In such cases as we have mentioned, it lasts only for an instant.

If, as before, a body is charged with + electricity, and a small body has a charge of one unit of the same kind, wherever this unit body may be in the field of force due to the other, it is under a force of repulsion. To bring it up to the + charge against this repulsion it must be pushed with a force that steadily increases as the unit body approaches the larger charged body. This is *doing work,* and if the unit is started from an infinite distance, or from a point that is outside the field of force, a definite amount of work is needed to bring it to the first body. This amount of work is called the electric potential of the body. Not only is this potential a fact, but by what-

ever path the unit charge may be brought, straight or tortuous, the same amount of work is required ultimately to get it to the charged body, and *some* work to take it to any point in its path. There is, therefore, a potential at every point in the field of a given charge, whether there is a body there or not. If the work is equal to one erg the potential is unity, and in general, the potential at any point is the number of ergs that measures the work of bringing a + unit to that point from without the field of force. If more work is required to bring the unit to one point than to another, the two points are at different potentials, and the difference of potential between them is the work required to take the unit from the point of lower potential to the higher one.

On the other hand, a plus unit charge would go of itself from the higher to the lower under the action of the electric field, and could do work equal in amount to the difference of potential, just as a material body falling in a gravitational field of force can do work. Difference of potential, therefore, represents energy.

CHAPTER XXXII

HOW ELECTRIC DISCHARGES AND ELECTRIC CURRENTS OCCUR

TWO bodies at different potentials are a system possessing energy so long as they are separated by a nonconducting medium. A layer or sheath of air or glass, or other nonconductor, through which electricity would have to pass to get from one body to another, is called a dielectric. The force from an electric charge, or the induction of another charge, is greater through some kinds of dielectric than others; hence the qualification "in air" in the definition of unit quantity. If the difference of potential between two insulated bodies is very great and the dielectric between them is thin or very imperfectly conducting, the strain of the effort to discharge electricity from one body to the other may be so great as to break through the dielectric, and a so-called "disruptive" discharge occurs, accompanied by a spark and an explosive noise. Energy is expended in this spark and noise, and the two bodies come to the same potential. If the bodies are joined by a poor conductor, like a wet thread of linen or cotton, the discharge is gradual, but they, as well as the link connecting them, will eventually come to a common potential; if they are connected by a good conductor, they come to a common potential immediately; if they and the body uniting them were perfect conductors, they could not have a difference of

potential. Whether the + electricity flows to the —, or the contrary, or whether both flow in opposite directions, it is conventional to assume that + electricity flows from a point of higher potential to one of lower, and we have now arrived at the base of electric discharges and transferences of currents.

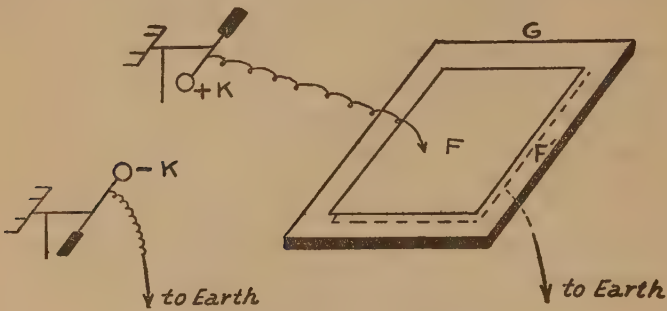
It is customary also to take the potential of the earth as an arbitrary zero or level of potential, a potential higher than that of the earth being positive, and lower, negative.

Electric difference of potential is the energy which causes an electric current.

Although air is not a conductor of electricity, individual particles of air or of any gas become electrified when in contact with a charged conductor, and by intermingling with other particles of the gas carry the charge away. Such leakage into the surrounding air is more rapid where the curvature of the conductor is shortest, or from edges or corners, and most of all from sharp points. It is difficult to bring a conductor to a very high potential if its terminals are fine points, and if a large charged sphere is close to a pointed conductor that leads to the earth, the charge on the sphere is neutralized either by passing continuously to the point and on to the earth, or else by a flow from the earth by way of the point to the charged sphere. To electrify bodies frictional machines were used at first, but although they serve interesting and valuable purposes in "static" electricity, their chief use is to charge "condensers," or to produce a powerful spark discharge, and both of these are now more commonly done by means of an "induction coil." The condenser consists of a thin sheet of glass, or mica, or other

dielectric—it may be simply a stratum of air—with a conducting sheet on each side of it.

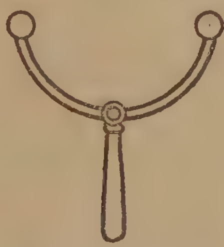
For example, G is a pane of glass with tin foil F, F′ on both sides; K, K are the knobs of an electrical machine, respectively, + and —. Suppose + K to be connected to one sheet of tin foil, and — K to the other; or both — K and the other plate may



(A) CHARGING A CONDENSER

be put to earth. As the machine is operated F receives a + charge. Through G this induces — electricity to the under surface of the glass and the corresponding + charge on F′ is repelled to earth or to the — K knob. If G is thick or F and F′ are small in area, a small quantity of electricity will bring the plate of the condenser to a high potential, but if F is very thin the + and — charges are so near each other that they almost neutralize the effect of each other at any point external to the condenser, and a + unit brought up to it would be almost as completely attracted by F′ as repelled by F; and the potential of the condenser would be small unless the charge were very large. As the machine is capable of producing a high potential difference between its terminals K, K, it may go on charging the condenser

until the quantity + and — on the plates is very great. The two sheets cannot discharge to each other for there is a large insulating area of glass beyond the edge of the metal, but if a bent wire with a glass or rubber handle, be used so as to touch F′ with one end and the other end is brought near to F, an intense brilliant spark discharge occurs with a loud report. The energy of such a discharge may be dangerous to life if one should inadvertently touch both plates of the condenser at the same time. In its older form a jar or bottle coated on both the inside and outside, as illustrated, was used, the external knob being in contact with the interior coating by a chain hanging within the jar. This is called a Leyden jar, from the fact that it was the form of condenser used in early studies of this kind,



(B) A DISCHARGER

in Leyden, by the Dutch physicist Musschenbroek. If the plate of Figure (A) had its central portion depressed and the sides bent upward all around it, it would then be a Leyden jar.

"CAPACITY" OF A CONDENSER

By the electrical "capacity" of a condenser or a conductor is meant the quantity of electricity needed to charge it to one unit of potential, or to increase

its potential by unity. This definition is similar to that of the capacity of a body for heat. The capacity of a condenser may be made greater by increasing the size of the plates or jars. As it is not practicable to carry this very far, the end is accomplished by building up a series of single condensers

(C) THE LEYDEN JAR IS A CONDENSER

with air, or insulators, between them, and joining all the upper plates to one terminal and the lower ones to another. That is equivalent to one condenser whose single plate is as large as all those that are united. With jars, a battery of any number may be used, all the external coatings resting upon a

common metal strip, and all the knobs joined by a metal rod or chain.

In the plate condenser and in the jar form the difference of potential between the plates may become so high as to strain the dielectric until a spark breaks through, and the glass is shattered.

A highly charged cloud floating above a square mile or more of the earth's surface induces on the earth itself and on the houses, trees, etc., a charge of the opposite kind. The surface of the cloud and that of the earth are the two plates of a great condenser with the air as the intervening dielectric. If the potential difference between these plates becomes extremely high, the condenser is discharged in a flash of lightning.

DR. FRANKLIN'S FAMOUS KITE—INVENTION OF THE LIGHTNING ROD

The effect of points in discharging conductors was learned early in the progress of the science. Dr. Benjamin Franklin, as also several French physicists, took up the question whether the lightning flash of a thunderstorm was of the same nature as the electric flash between two highly charged bodies. It is now just about a hundred and seventy years since Dr. Franklin performed his celebrated "kite" experiment, which proved the identity of these two phenomena. After several attempts he succeeded in sending up a kite just as a thunderstorm began. The kite, which was made of silk, was surmounted by a sharp metallic point, and the cord of linen thread from it became wet and was a fairly good conductor. He took the precaution, however, to have the lower portion of the string, which he held in his hand, of silk, and at the junction of linen and silk he hung a

metal key. Quietly and imperceptibly this was charged with electricity of the same kind as that on the cloud, while the earth and objects upon it were charged by induction oppositely. On presenting his knuckle to the key from time to time, Franklin drew snapping sparks from it precisely as from the knobs of the friction machines then in use for experimentation. This led to the invention of the lightning rod.

Just how efficacious this instrument is cannot be known, as we cannot tell what might have happened without it, but there is no doubt that under certain circumstances it is of great value. At its lower end the rod should be led into moist earth, and protection would be much better assured if the rod or rods branched into a network of conductors about the building, like vertical bars of a cage. Clouds, and the air around them, become heavily charged with electricity, and induce a charge of the opposite kind upon the earth and bodies on it beneath the clouds. These are silently but continuously discharged by the pointed conductors, without reaching the potential that would cause the disruptive discharge—the lightning stroke.

CHAPTER XXXIII

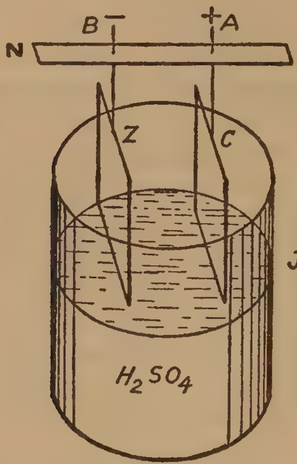
ELECTROKINETICS—ELECTROMOTIVE FORCE

ALTHOUGH electrostatic charges and disruptive discharges are vital factors in recent developments of the science, especially in wireless signaling and in so-called radio action, the largest part of the applications of electricity to-day are accomplished by electricity in motion or electric currents.

Some special physical or chemical action is necessary to produce and to maintain an electric difference of potential between two bodies or two parts of one body. It may be brought about through various agencies—mechanical, chemical, thermal, or magnetic. When a conductor—a wire, for example—connects two bodies differing in potential, a transfer or passage of electricity along the wire results. This is an electric current. The extent to which an agent is capable of producing an electric difference of potential (P. D.), is its "electromotive force" (E. M. F.)

If a plate of copper and one of zinc, with metal terminals A and B, are supported by a nonconductor N, in air, they will not show any difference of potential or electric charge. If they are lowered into a vessel J containing dilute sulphuric acid, a slight chemical action upon the zinc will occur which will soon cease, and then it will be found by a delicate test that A is electrified positively and B negatively,

with charges of static electricity. The materials thus assembled constitute a voltaic cell or element, with an electromotive force that has brought about a potential difference between A and B. But the extent to which it can do this is limited and definite; the P. D. will be the same whether the plates are large or small and whether the vessel is filled with



CHEMICAL ACTION ONE SOURCE OF ELECTROMOTIVE FORCE

the liquid or contains only a few drops. The E. M. F., then, depends upon the nature of the materials, and not upon their size or quantity. A and B are called the poles of the cell, and several cells or elements together make a battery, though sometimes the term "battery" is applied to a single cell.

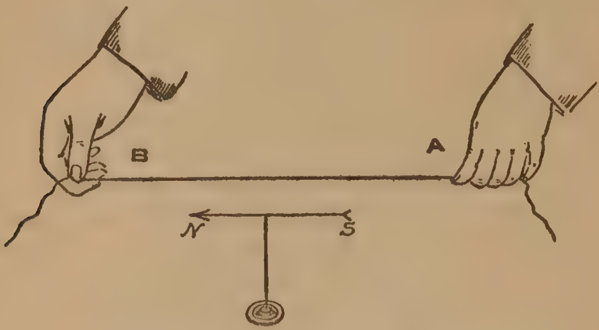
By connecting the terminals A and B with a condenser of known capacity, its plates will receive charges of + and — electricity until the potential difference between them is as high as this cell can

produce. With any such battery cell, however, this would not be more than about one four-thousandth as great as that between two metal balls a half inch in diameter, with a static charge on them sufficient to spark across an air gap of as small as one twenty-fifth of an inch.

The current can only flow continuously when there is a complete circuit of conductors, as from A to B outside the cell, and from Z to C within it. If this circuit is broken anywhere, say between A and B, electricity will flow into the two parts of the connecting wire (which may be miles in length) until its terminals are brought to a P. D. equal to the E. M. F. of the cell. When the ends are united or the circuit is closed and the plates are immersed, chemical action will be resumed in the liquid, and a current will flow in the wire, but if the plates are raised out of the liquid they come to a common potential, and the current ceases: i. e., it flows only while the E. M. F. is effectively maintaining or renewing a difference of potential. While it is flowing, the conductor joining A and B will be found to have acquired new properties. In the first place this will rise in temperature, showing that energy has been expended upon it; but far more significant is the change that occurs in the region around the wire.

With the magnetic needle NS at rest, and a portion of the conductor AB held above the needle, while the circuit is open no effect is perceived, but upon closing the circuit the needle is immediately deflected and settles to rest in a new position transverse to the wire. Wherever the conductor is placed alongside of the needle, the latter tries to take a transverse position. With any displacement, however, the force

of the earth's magnetic field is exerted to draw it back into its normal position, and the effectiveness (or moment) of this increases the farther the needle is deflected, and the needle presently reaches a new position of equilibrium, depending upon the distance



A CONDUCTOR TRANSMITTING A CURRENT EXERTS A MAGNETIC EFFECT

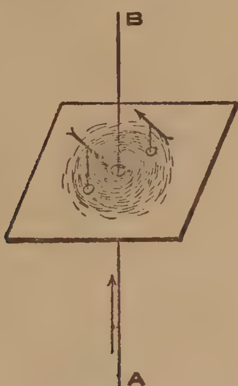
from the conductor and the energy with which this has become newly possessed.

No body will change its condition of rest or of motion of itself, and a magnet at rest will not move from its position, except under the influence of some force, and the deflection of the needle is evidence of a magnetic force brought to bear upon its poles.

Again, if the conductor AB is led through a plate of some material that is nonconducting and non-magnetic, as cardboard or glass, as in the diagram, and iron filings are scattered upon this plate, when the circuit is closed these filings will arrange themselves in rings or whorls. A magnetic field has been created around the conductor like a cylinder encircling it with the wire as its axis, and its lines of force everywhere concentric rings. The field is

most intense near the axis, and the force upon a magnetic pole greatest from that portion of the conductor nearest it. If the conductor were circular in form, instead of straight, every part of it would be equally distant from the center, and a magnetic pole there would be urged equally by every element of the current.

Observe that neither the iron filings nor the magnetic poles are attracted to the conductor or repelled from it; each filing becomes a minute magnet, and they all link themselves in rings around the conductor. The current is assumed to be from the + pole of the battery to the — in the external wire, and the direction in which the needle will be deflected may be determined by Ampère's rule: "If



MAGNETIC LINES OF FORCE

the observer is swimming *in* the current, *with* the current, and facing the needle, the north pole is deflected to his left hand." That direction may be carried in a circle around the wire, and the circular line thus traced out will be a magnetic (not electric) line of force. Other mnemotechnic rules have been

chosen. One employs the letters of the word "snow" —S, N, O, W—as initials of the words South, North, Over, West. "If the current is from the South, to the North, Over the needle, it points West; and the necessary changes in the rule are easily worked out to suit other positions of the needle and current.

This magnetic effect was discovered by the Danish physicist, Hans Christian Oersted, in 1819. Until that time it was not known that any relationship existed between electricity and magnetism.

CHAPTER XXXIV

UNITS AND MEASUREMENTS OF ELECTRIC CURRENTS

THESE effects could not be turned to account in a scientific way until they could be measured and compared accurately. A unit was accepted for measuring the quantity of electricity in a static charge, and the quantity discharged along the conductor per second would measure the rate of flow, or the strength of the current; but in dealing with magnetic effects it was more convenient to rate the strength of a current directly by its magnetic action. It was found that if a further portion of the wire AB—in the figure on page 274—were placed along with AB, duplicating it, the effect on the needle was doubled, trebled with three such lines, and so on. With the wire in the form of a circle, the lines of force are perpendicular to the plane of the conductor at the center. In the central portion, for a distance not more than one-tenth as great as the radius of the circle, the field is practically uniform.

Suppose the small magnet NS to be suspended by a fine silk thread having no twist, and when it settles to rest in the plane of the magnetic meridian the wire circle is turned with its plane in the same position. The magnetic lines of force from NS are now chiefly in the direction of the needle. If a current flows in the wire from A to B, its lines of force are as in the figure, the arrows showing the direction

in which a + magnetic pole would be urged, those at the center pointing west, and the needle turns in that direction. Always magnets and conductors with magnetic fields of force seek so to place themselves that their lines of force shall be parallel.

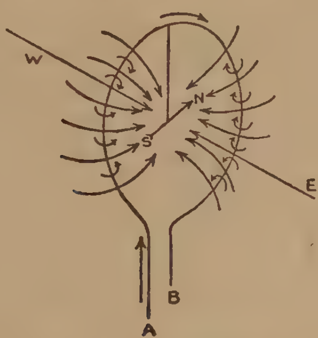
The unit magnetic pole has already been defined, and for electromagnetic measures, unit current is defined as a current of such strength that, flowing in a circle of one centimeter radius, it exerts on a unit magnetic pole at the center a force of one dyne for every centimeter of the circumference.

Early in the efforts to systematize electrical and magnetic measurements, the practice was instituted of naming the various units after men who had distinguished themselves in the development of the science. For the unit just defined there is no special name; it is called the c. g. s. unit, or the electromagnetic unit of current strength, but a current one-tenth as strong as this is adopted throughout the world as the "practical unit" current, and is called an *ampere*, after the French physicist, André Marie Ampère.

ACTION AND REACTION BETWEEN AN ELECTRIC CURRENT AND A MAGNET

Instead of a single loop as previously described, the wire may be wound in a coil, and the current in each turn will produce its magnetic field, so that this may be made very strong by using a coil of many turns, and of small radius. When the coil carrying the current, and the magnet in its field, react upon one another, under the third law of motion, by whatever force the conductor pushes the magnet, by just so much force the magnet reacts to push the wire. If the conductor is fixed and the

magnet is pivoted or suspended, the needle is deflected; if the magnet is fixed, and the coil of wire conductor is suspended between the poles of the magnet, it is the coil that will turn when a current passes around its circuit, and will endeavor to place itself so that the lines of force due to the current will coincide with those due to the magnet. Any instrument which shows the strength of current by



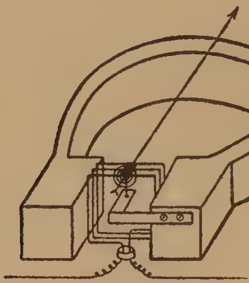
MAGNETIC FIELD AT THE CENTER OF A CIRCLE AROUND WHICH A CURRENT IS FLOWING

the mutual action of the current and a magnet is a galvanometer. If it is so proportioned and has its scale so divided that its readings are the number of amperes in the current, it is an ampere meter, or more briefly an *ammeter*.

If the coil were suspended by a fine wire the torsion in this would react against the deflecting force, but if it were pivoted as in the ammeter diagram, with no restoring force, it would turn through an angle of 90° with any current, so in this type of instrument the movement of the coil is restrained by a delicate spiral spring, which brings it to its zero position when no current is flowing. In com-

mercial ammeters the current at the one terminal is divided, a definite small fractional part going through the coil, and the other part passing to the other terminal by a heavy conductor as a by-pass, or shunt.

In electromagnetic measure the unit quantity of electricity is the quantity carried per second past any section of a circuit in which unit current is



ACTION OF AN AMMETER

flowing. In comparison with the unit already defined for static electricity, this is a very large quantity, and the "practical" unit that is used is one-tenth as great as the electromagnetic, and is called a *coulomb*, after the French physicist, Charles Augustin de Coulomb.

The unit for potential difference is such a difference between two points that one erg of work is required to transfer the unit quantity from one point to the other. This is the same amount of work as had to be done in the electrostatic measures, and as the quantity here to be transferred is so many times greater, the potential difference must be correspondingly smaller. The "practical" unit employed is 100,000,000 times as large as the electromagnetic unit, and is called a volt, after the

Italian physicist, Alessandro Volta. The same unit is used for electromotive force.

ELECTRICAL RESISTANCE; OHM'S LAW

It soon became apparent that the nature of the conductor had a great deal to do with the strength of current that would flow through it under a given electromotive force. With the same E. M. F. the current was quite different with conductors of like size but unlike material, and also with conductors of the same material but differing in size. With a copper wire one foot long a much stronger current was obtained than with a wire a thousand feet long, and with two wires of the same length and material, the thinner showed the weaker current. This difference in conducting was attributed to some quality in the conductor which impeded the passage of electricity and so was called its "resistance." But resistance in a conductor is merely failure to conduct; if it conducted perfectly the resistance would be zero, and if it did not conduct at all its resistance would be infinite. As no material does conduct perfectly, every body offers some resistance to the passage of a current. It might have been better to determine the merit of a conductor by its readiness to conduct; that quality would be its conductance, and the measure of the resistance would be the inverse of the conductance. The idea of resistance and the name, however, have become too strongly established to be displaced. The relation which resistance bears to both E. M. F. and current strength was discovered by the German physicist, Georg Simon Ohm. It is that the current, I, in a conductor is directly proportional to the electromotive force, E, and inversely proportional to the resistance, R. This is known as

"Ohm's law," and has undoubtedly been the most important and most fruitful of all laws of electric currents. If we choose for a unit by which to measure resistance, the resistance of a conductor that transmits a unit current when the ends of the conductor are at unit difference of potential, or that has unit E. M. F., then in such terms, always, for a steady current, $I = \frac{E}{R}$. The unit of resistance has been so chosen. In practice it is such a resistance that with an E. M. F. of one volt applied to it, a current of one ampere flows through it. This unit is called an *ohm*, and $I\ (\text{amperes}) = \frac{E\ (\text{volts})}{R\ (\text{ohms})}$.

A charge of static electricity is found to reside altogether on the surface of a conductor; it will spread itself over the outside surface, or be discharged as readily if the conductor is a hollow shell as if it is solid. It is different with an electric current. In a current the electricity utilizes the whole body of the conductor. The wire will transmit a current better in proportion as its area of cross section is greater. One conductor of the same material and length as another, but with twice as great a diameter, will have four times the area and will convey four times as strong a current with the same difference of potential between its ends; its conductance is greater, or its resistance is less. The resistance is inversely proportional to the area of cross section.

The practical electrician of to-day, at least in America, is as likely to speak of the size of wires in "circular mils" as in gauge number or inches in diameter. If the reader were to approach such a "practical" electrician for information as to suitable

size of wires and their relation to currents they were to carry, his answer would probably deal with circular mils. This is a compromise invented to evade the awkwardness of English units, and to use in a simple way the fact that the area of cross section is proportional to the square of the diameter. A "mil" is a thousandth of an inch, and "circular mils" (C. M.) means the square of the diameter in mils. If the diameter is one-thousandth of an inch, the size of the wire is one circular mil. If the diameter is one-tenth of an inch, i. e., 100 mils, the square of 100 is 10,000, and the size of the wire is 10,000 C. M., and so on. Wires of the same material and equal length will conduct in proportion to their size in C. M.

With the same material and cross section the resistance is directly proportional to the length. Besides the effect of length and thickness on conductance, there is a specific power to conduct, for each material, so that of two conductors of the same length and cross section but of different material, one has a higher resistance than the other. Silver is the best conductor, and next to that, copper. Taking the resistance of silver as unity, that of other substances is as follows: Copper, 1.06; aluminum, 1.8; brass, 5.6; iron, 6.6; platinum, 7.3; nickel, 7.4; mercury, 60; gas carbon, 3,000.

THE PRACTICAL UNITS IN USE THROUGHOUT THE WORLD

The f. p. s. system of mechanical units is based upon the foot for a unit of distance, but in large practice, with railroads for instance, a unit 5,280 times as great is preferable; it is a mile. One pound is oftentimes suitable for determining weight or mass, but in freight service a unit 2,000 times as

great is employed; it is a ton. In like manner, the well-connected, scientific scheme of electromagnetic units for electrical measurements is replaced by another system called "practical units" which are multiples or divisions of the fundamental c. g. s. units. These have been legalized, and are defined by international agreement, in accordance with certain physical conditions, and certain electrical principles and actions, so that they could readily be replaced if the standards were lost or destroyed. The principal ones are as follows:

INTERNATIONAL LEGAL STANDARD UNITS

The ohm, the resistance offered to an unvarying electric current by a column of mercury at the temperature of melting ice, weighing 14.4521 grams, of uniform cross section, and having a length of 106.3 centimeters.

The ampere, that current which, under certain specified conditions, should deposit silver from a solution of silver nitrate, at the rate of $\frac{1,118}{100,000}$ of a gram per second.

The volt, the $\frac{1,000}{1,434}$ of the electromotive force of a Clark cell set up according to certain specified conditions, and kept at a temperature of 15° C.

The coulomb, the quantity of electricity conveyed by one ampere during one second.

The farad, the capacity of a condenser charged to the potential of one volt by one coulomb of electricity. (This unit is named after the English physicist Michael Faraday.)

The joule, the quantity of energy expended per second in one ohm by a current of one ampere. (It is so named in honor of Dr. James Prescott Joule of Manchester, England.)

The watt, the rate of work represented by one joule per second. (Named for the famous Scotch engineer, James Watt.)

The henry, the induction of a circuit in which a variation of one ampere per second induces an electromotive force of one volt. (So named because of important discoveries in electromagnetic induction by the American physicist, Joseph Henry.)

CHAPTER XXXV

THE EVOLUTION OF THE ELECTROMAGNET

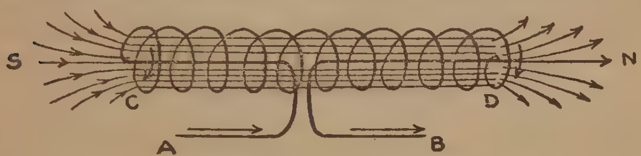
IT is at once a mystery and a triumph of science to be able to create or to destroy a field of force of unbounded possibilities! Yet this is what the electrical engineer can do, and the power so to do has revolutionized the industrial practice of the world in less than half a century. Because of its diversity as well as its magnitude, electromagnetism surpasses the steam engine in its consequences.

If a wire conductor AB is wound along the surface of a cylinder, thus making a helix, and a current is passed from A to B, each turn of the wire produces a magnetic field with its own lines of force, the general effect of which is a continuous direction of the magnetic field within the helix from one end to the other, the lines emerging from one end and bending around and reentering the other end. The coil is virtually a succession of parallel rings, or so-called "magnetic shells." Such a coil is called a solenoid.

After the first great discovery of the fact that an electric current produces a magnetic field, the next surprise was that a solenoid, say of copper wire, carrying a current, is itself, to all intents and purposes, a magnet, with its north and south-seeking poles, although its material is nonmagnetic, and there is nothing magnetic whatever in its make-up! If suspended about its middle, it will orient itself

in a north and south direction just as a magnet does, and if its ends are presented to the poles of a magnet, it will attract or repel them precisely as another magnet would. Facing the end of the solenoid, that end around which the current is moving clockwise is the south pole. With the cessation of the current all these manifestations cease, and the helix becomes simply an inert piece of copper.

The interior of the helix, occupied only by air, is a magnetic field, and we have already seen that all that is necessary to make a magnet of a piece of

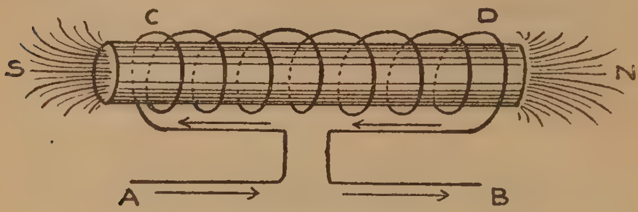


MAGNETIC FIELD OF A SOLENOID

iron is to place it in a magnetic field. So, not only is the solenoid a magnet, but if a bar of iron as CD, is inserted in the coil, it is magnetized. The strength of pole represented in the first solenoid figure was not very great, even with a moderately strong current; the strength of pole of the bar CD, in the next figure, is astonishingly great. The number of lines of force in the solenoid is multiplied many times in the magnetized iron core of the helix. Iron is said to be much more permeable to magnetism than air. A magnet thus produced by an electric current is an electromagnet.

The freer the iron is from carbon, i.e., the "softer" it is, the more strongly it is magnetized. The magnetization, through a considerable range, is proportional to the strength of the current and the number of times it encircles the iron; it is, therefore,

determined by the product of these two quantities, and obviously that product expresses the strength of field engendered within the solenoid. If the current is given in amperes, this product is called "ampere turns." A current of 5 amperes encircling the core 100 times would have the same magnetizing action



AN ELECTROMAGNET

as one of 25 amperes making 20 turns; but the iron in such cases would be magnetized in that proportion up to a certain point only, for there is a limit beyond which the magnetization of any given piece of iron cannot be carried at all. When it reaches that point the iron is said to be saturated.

As in the case of the permanent magnet, if the electromagnet is to be used for the sake of the mechanical force which it can exert, such as lifting or pulling, or if it is wanted for the sake of the magnetic field that may be produced between its poles, it is commonly put in the form of a yoke or a horseshoe without any change in the winding of the conductor about it. Note particularly, however, that the current does not pass through the iron that is magnetized, but around it; the wire with which the core is wound is completely insulated by its covering of silk, or paraffined cotton.

In the yoke form the wire is sometimes wound upon spools that can be removed from the iron if

desired. The pole pieces may have any desired shape, and be brought near each other. When massive in construction, and with a magnetization of many thousand ampere turns, such magnets are used in lifting heavy pieces of iron or bodies to which they are attached, which by their form or position would be difficult to handle in any other manner.

It is a powerful permanent magnet that can lift fifteen times its own weight, and it is not feasible to make a very powerful steel (permanent) magnet of great size. Moreover, its lifting force decreases rapidly in proportion to its own weight as the weight is increased. Even if a very powerful permanent magnet were available, its continual influence upon iron in its neighborhood would make it a good deal of a nuisance. On the other hand, an electromagnet

ELECTROMAGNETS

of large size that can lift ten to twenty times its own weight is not exceptional, and can easily be constructed of a ton or more in weight.

THE WONDER OF THE ELECTROMAGNET

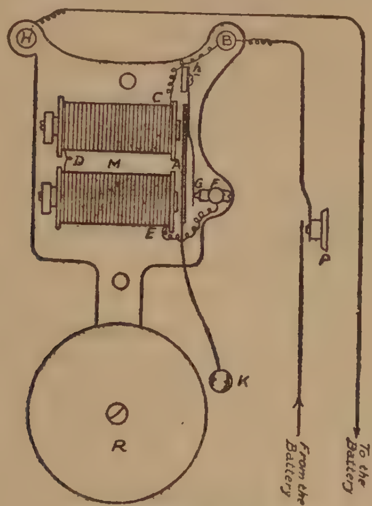
While permanency is in some cases a very desirable feature in a magnet, the ability to get rid of

its magnetic quality and to restore it again, at will, is a far greater advantage, and therein lies the highest merit of the electromagnet. It can be made or unmade at pleasure, for it is a magnet only while the current is flowing, and ceases to be such immediately upon the stoppage of the current. Like a powerful genie, subject to the beck and call of its master, it appears when he summons it and vanishes when dismissed. Evincing almost a human sense, its superhuman powers make it uncanny. And these powers have been put to use in every conceivable form and for every purpose of civilization. It is the effective agent in ringing the doorbell, or calling the office boy, and is indispensable to the wireless transmission of intelligence, as well as to the telegraph and telephone. Every dynamo for the greatest lighting systems, every electrically driven engine, from the powerful electric locomotive to the diminutive motor operating the sewing machine or the dentist's drill, owes its action to the electromagnet, and its efficacy to the fact that this can be made or unmade or even reversed, at the will of the operator—in many cases even he can be dispensed with, and with human intelligence to control the supplying of the electric current, the machine will do its work automatically!

The construction and operation of the common electric bell is illustrated and described in detail because it is typical of various applications of electromagnetism in signaling.

Mounted on an iron frame which carries the bell R is the electromagnet M with its two spools, the ends of the cores showing at the right. The winding, with covered wire, leads from the post B, which is insulated from the metal frame, to the spool C,

thence to D, to E, and to the post F, which is also insulated. An iron armature A, in front of the pole pieces, has a spring G, which presses gently against the screw passing through F. The armature is extended by a light rod to carry the hammer K, and



THE ELECTRIC BELL

at the other end is connected by a spring to a stud h, and is, therefore, electrically continuous with the other post H, that is fastened directly to the frame. Somewhere, out of the way, is a battery of two or three cells, whose wires lead to the posts B and H. The circuit would be complete but that a gap is left in one of the wires, where the signal is to be given—by the side of the door if it is a doorbell. Contact is made and the circuit is closed by pushing a button as at P, where the circuit is open.

Immediately the cores are magnetized, and the armature A is drawn toward them. This opens a

gap at G, the current stops, and the magnets cease to attract. The armature springs back into contact with F, to be again pulled away by the magnets, and the operation goes on until the button P is released. With every vibration of the armature the bell is struck by the knob K.

The operator may beat any sort of tattoo with the push button. He may make his contacts short or long in duration, and follow a code of signals as the telegraph operator does in sending his messages.

HOW THE TELEGRAPH OPERATES

The next diagram shows the arrangement for the simplest kind of telegraph line. The apparatus is the same at both stations. As here shown A is the sending station. When proper connections are made, one pole of a battery is connected to the line, and the other pole to the earth. At the other station the line is led directly to earth, or if another battery is used it is joined in as if in continuation of the first one, and one of its poles is put to earth. The earth, then, takes the place of a return wire to complete the circuit. To send from B, the switch there should be open and that at A closed.

The depression of the key at A makes electric contact, like pressing the push button of the bell; the current along the wire actuates an electromagnet at the receiving station, and this pulls the armature, making a sharp click; or if it is connected with a lever that carries a pencil point under which rotates a drum with paper, it makes a mark upon the paper. The magnet making the clicking noise is called a sounder; that making the tracing a recorder or recording apparatus. If the sending key is in contact only for a moment the record is only a dot on the

paper, and this may be followed by other dots at longer or shorter intervals. If the key is held down longer the record is a dash, and the whole message is a succession of dots and dashes. Either a dot or a dash is only a click on the sounder, but the release of the armature is attended by another sound somewhat different in character, thus indicating a brief or a prolonged signal, and still other established periods mark the intervals between words. The

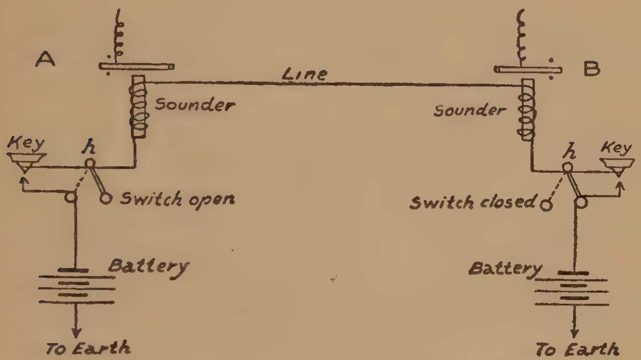


DIAGRAM OF A SIMPLE TELEGRAPH LINE

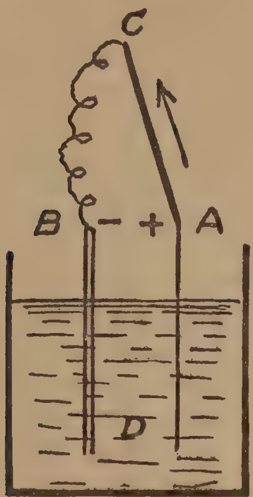
scheme of dots and dashes in common use for the various letters is the Morse code, and the words are regularly spelled out according to this code, the skilled operator receiving the message by sound quite as well as by the record.

In a long line the resistance is great, and the current from the battery may not be strong enough to make a distinct signal at the receiving station. In such case an auxiliary magnet called a relay takes the place of the sounder. This is sensitive enough to respond to a weak current, and its armature is part of the circuit of a local strong battery that

also includes a regular sounder. The movement of the armature of the relay closes the circuit of the local battery and this furnishes a strong enough current to operate a sounder or a recorder. In all these magnets, when the current ceases the armature is drawn back by a spring.

To put a quantity of electricity into a conductor at a point with a higher potential than another point (or, if it is there, to give it the necessary energy of motion) means to do work. If the two points have a potential difference of one volt, and the unit quantity, a coulomb, passes from the higher to the lower point, it can do work to an amount called a volt-coulomb. The name for this amount of energy in electrical parlance is the "joule." It is equal to 10,000,000 ergs. In a current of one ampere, this much energy is expended every second in the part of the circuit joining the two points, and the current will not continue unless the supply is renewed or maintained from some source. The source is sometimes called the "generator"; its energy in maintaining the difference of potential is its electromotive force. Since electromotive force and difference of potential are both measured as energy, they are commonly taken to mean the same thing and are used as interchangeable terms. If ACBDA, page 295, is a complete circuit with a current flowing as indicated by the arrow, it is flowing everywhere around the circuit; there is a resistance in any and every portion of the circuit, and there is a difference of potential (frequently called fall of potential) between any two points; very small perhaps between A and C, larger between C and B, and Ohm's law tells us that the current, which is equally strong everywhere, is the ratio of the potential difference

between any two points to the resistance between those same two points; there is but one electromotive force, that of the cell, and the same current strength is the ratio of the E. M. F. to the entire resistance



E. M. F. IN AN ELEMENTARY BATTERY

of the circuit. Electromotive force arises from chemical action, or heat, or mechanical effort. In voltaic batteries chemical action within the cell is the source.

Almost any combination of materials in which chemical action occurs will develop electromotive force, and for a while experimenters seemed to have a mania for making new kinds of batteries, but the combinations that amount to anything of consequence and are readily available have been sifted down to a few types. In the very elementary form illustrated, when the circuit is closed, the current is not only a passage of electricity from A to B externally to the cell, but a flow from one plate to the

other within it. For this, the liquid must be a conductor. Pure water is not such, but if it contains only a small quantity of an acid, or an inorganic salt, it acquires the power of conducting. In the process of transferring electricity through the liquid the water of the aqueous solution of sulphuric acid is decomposed, oxygen attacks the zinc and hydrogen is liberated at the copper plate. This gathers on the copper in fine bubbles, and makes a nonconducting layer of gas, which checks the action of the cell. Besides this, the hydrogen is electrically opposite in sign to the zinc, and so tends to send a current in the opposite direction, or to reverse the polarity of the cell. These two effects constitute "polarization"—and every cell polarizes somewhat. Substances are used in some cases which react chemically or mechanically to take up the hydrogen as it is freed, and so prevent polarization. In other cases, where the cell is wanted for continuous action of only a few seconds at a time, this defect is not serious, as the constituents readjust themselves quickly while the cell is at rest. They are used for "open circuit" work, such as telegraphing, telephoning, bell calls,etc.

CHAPTER XXXVI

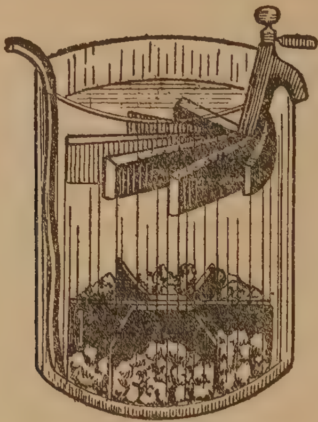
BATTERIES

ONE-FLUID AND TWO-FLUID CELLS

THE most satisfactory cell that uses a single fluid is the sal ammoniac cell. This is a glass jar containing a saturated solution of ammonium chloride (sal ammoniac), into which dip a rod or plate of zinc and one of carbon prepared usually from coke or charcoal. The carbon is not attacked by the solution, but the zinc is eventually eaten up. The two solids in the cell are technically called "electrodes," carbon being + and zinc —. The E. M. F. of the sal ammoniac cell when fresh is about 1.45 volts. When two liquids are used they are commonly separated by some porous material like an unglazed earthenware cup, or one of the liquids rests upon the other that has the higher specific gravity with no septum between them. This is the case with one of the best types of battery in use. It is called a "gravity battery" and is not portable. Each liquid contains its own appropriate metal plate. In the gravity cell, a plate of zinc is immersed in a weak solution of zinc sulphate, and a copper plate in a strong solution of copper sulphate.

Besides the batteries already described there are two other types constantly in use. One is familiarly termed the "dry cell." This, while containing no liquid, is not altogether dry; at least its contents are sufficiently damp to make them conducting.

The dry cell consists of a cylinder of thin zinc with a binding post which is the negative pole. Within this cylinder is a prism of gas coke or carbon compressed into a solid rod, whose terminus is the positive pole, and around this is packed a mixture of lime



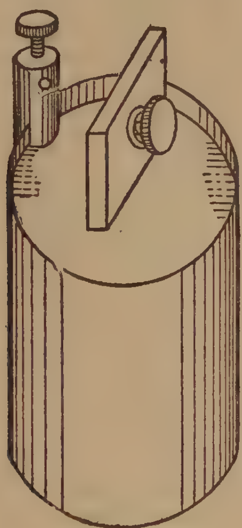
GRAVITY BATTERY

and granules of peroxide of manganese, that acts as a depolarizer. The whole is sealed by a layer of pitch over the top, and the cell is portable in any position. These dry cells, when fresh, have an electromotive force of about 1.5 volts. They polarize rapidly and cannot be used continuously for more than a few minutes. They are, therefore, of service chiefly for open circuit work, but depolarize quickly after action ceases. They are made of various sizes, and are especially popular in flashlights.

THE STORAGE BATTERY

The storage battery is sometimes regarded as storing up electricity, but this is not the case. It is primarily inactive, and only transmits a current

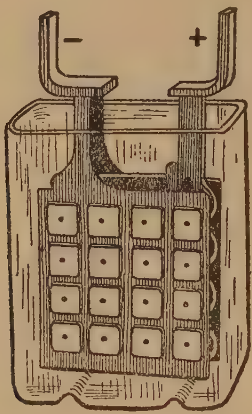
after it has been put into a condition to do so, or is "charged," by the passage of a current through it from some other source. Hence a cell of this kind is known technically as a "secondary" cell, while those which produce a current in the first place by the nature of the materials composing them are called "primary" cells. In the storage cell the plates are put into such a condition chemically as to make of them a battery with a definite E. M. F. Chemical energy is stored up to be given out afterward electrically. In the most common form the plates



THE DRY CELL

are lead, in a dilute solution of sulphuric acid. When a current from some extraneous source is passed through it, one plate becomes coated with lead peroxide; the other simply with spongy lead. This change of condition will go on until the terminals of

the plates have a potential difference of about 2.2 volts, when the cell is said to be "charged." It may now be used as an independent battery and will supply current until its E. M. F. has dropped to about 1.8 volts, when it must again be charged. All storage batteries are secondary and are sometimes called "accumulators." Besides the lead-acid type, another



THE STORAGE OR SECONDARY CELL

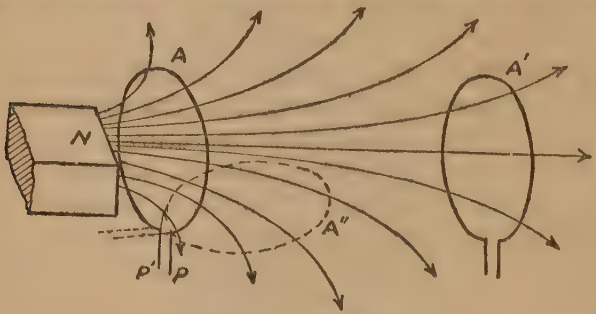
popular form is considerably lighter and not so expensive, in which the plates are iron for the negative and oxide of nickel for the positive, in a solution of caustic potash. Its E. M. F. is about 1.2 volts.

A main conductor from one terminal of a generator may divide into several branches that reunite before reaching the other terminal. The entire current will then distribute itself among the various branches in proportion to their conductance, i. e., in the inverse ratio of their resistance. The various means of proportioning partial circuits, and measuring the particular part each one takes in an electrical system, is the work of the electrical engineer. With the help

of auxiliary resistances, different branches can be very delicately balanced against one another. Spools of wire wound in such length and size as to have various resistances may be inserted in a circuit to make up a resistance of any desired number of ohms. The instrument by which the comparisons are most frequently made is known as the "Wheatstone's bridge" and is constructed in different forms. For the electrical engineer the "bridge" is his balance, and he would be as badly off without it and his boxes of resistances as the chemist or the druggist without his balances and his weights. The resistance of a conductor varies with its temperature, and in one special form of the bridge, called a bolometer, one branch of the circuit is a fine strip of platinum. So exquisitely sensitive is the resistance of a conductor to change of temperature, that with the bolometer Professor Langley was able to measure the heat of moonbeams! It is possible thus to measure one-thousandth of a degree Fahrenheit, and to detect a change much smaller than this.

After it was learned that a current in a conductor sets up whorls of lines of magnetic force, just like lines representing the strength of magnetic poles, and that if the conductor is in the form of a loop or helix, these lines thread through the loop in greater or less abundance, the question naturally arose whether the reverse was true; whether the introduction of such lines in a loop would result in a current in the wire. It is a common impression, and not an uncommon statement, that the movement of an electric conductor so as to cut magnetic lines of force will engender an electromotive force in it, and that if it is a complete circuit, it will produce a current. But the statement that such movement will produce a

current is not quite correct. What happens is this: A conductor, as A, may have many lines passing through it and no current, or no electromotive force to make a difference of potential between P and P′, so long as it is at rest; but if it is moved to the position A′, many lines will be cut out, and the number passing through the plane of the loop will be greatly diminished. While this change



ELECTRIC CURRENT

Current produced by change in the number of magnetic lines of force passing through the space enclosed by a conductor

in the number is in progress an E. M. F. is developed in A, or if P and P′ are united, a current flows. If the loop had at first been in the position A′ and was then moved up to A, the effect would have been an E. M. F. or a current in the opposite direction. In every case this lasts only while the number of lines is being increased or decreased, but it will ensue upon any action that does so change the number of lines. If A were turned into the position A″, or from A″ to A, it would occur; and the number of lines so changed is counted for every turn of wire in the windings of the coil. If it has a hundred turns, it is reckoned that a hundred times as many lines are cut as if it had but a single turn.

CHAPTER XXXVII

INDUCED CURRENTS

INDUCTION COIL

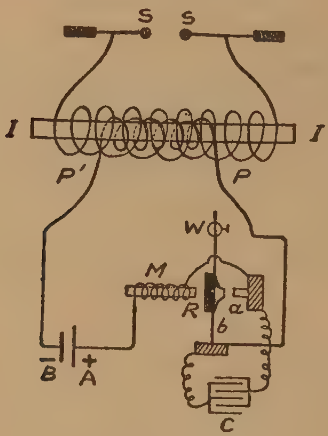
INTO a coil of many turns thrust the pole of a magnet—momentarily an E. M. F. is set up; withdrawal of the magnet causes an E. M. F. in the opposite direction. How great an E. M. F. is produced depends upon the rate, i. e., the number of lines per second introduced into the circuit or taken out; the stronger the magnetic field and the more quickly it is produced or destroyed, the higher the E. M. F.

The quickest and most effective way to put a magnet or a great number of lines through a coil is to use an electromagnet, and wind another coil about that. The electromagnet can be made and unmade instantly by manipulating a key, and every such make and break results in an E. M. F. in the outer coil. This is an induced E. M. F. and an apparatus to act thus is an "induction coil."

The figure on the next page shows the construction and operation of the induction coil. II is an iron core; PP′ is a thick wire of a few turns around this core, and supplied with a current from a battery AB. The current excites a small electromagnet at M and is led into a stud at *a*. Here, almost touching *a*, is a spring *b* carrying an iron armature R. From *b* the wire P continues, encircles the core II, and returns to B. Around II and its winding is another

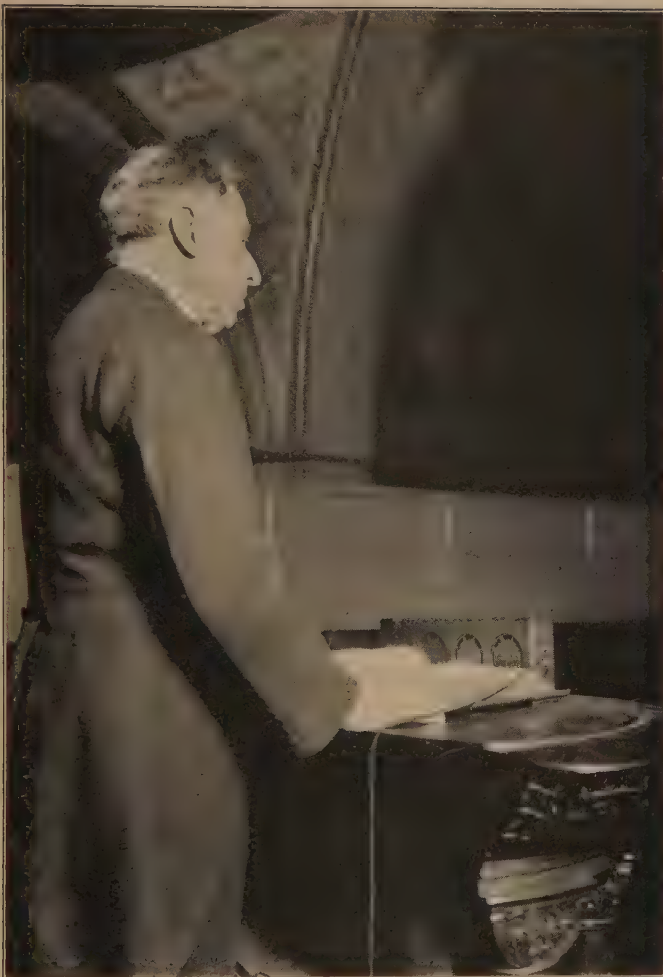
coil of many thousand turns of fine wire, very completely insulated from one another, and terminating at SS. The windings of PP′ form the primary coil, those of SS the secondary.

On putting *b* into contact with *a*, the circuit is closed and II instantly becomes a strong magnet. This induces a high E. M. F. in the secondary, and SS acquire so high a potential difference as to cause a



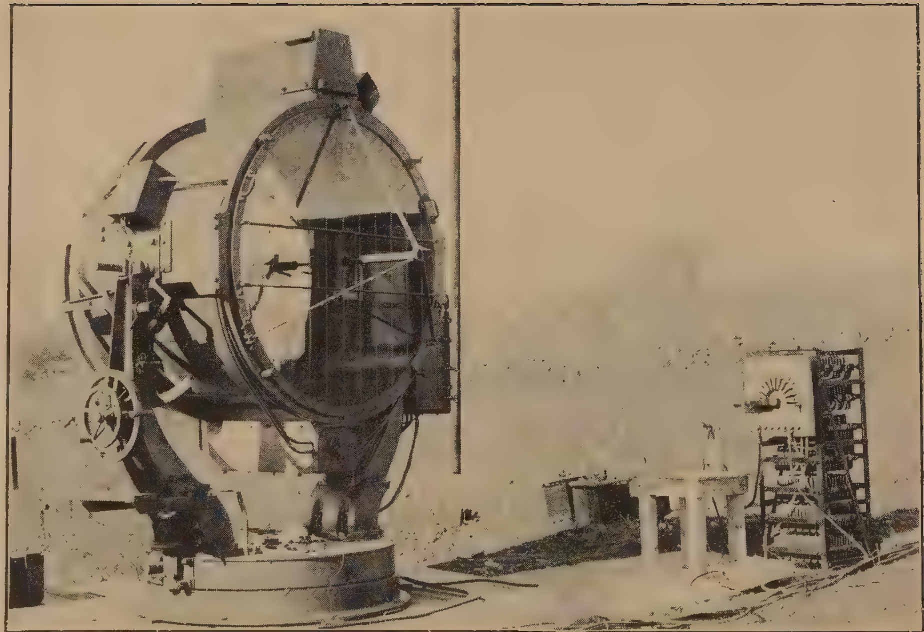
INDUCTION COIL

spark discharge between them. But M becomes a magnet also and immediately pulls the armature R to it and breaks the circuit at *a;* this demagnetizes II, and again an E. M. F. is induced in the secondary, but this time in the opposite direction: *b* springs back into contact with *a* and the operation is repeated, *a b* acting just like the spring of the electric bell. The rapidity with which *b* vibrates can be regulated by a weight W which may be fastened at different positions on *b* by a set screw. When the circuit is broken, a spark at the gap between *a* and



SERMONS BY RADIO

A preacher whose sermons are broadcasted by radio. The acousticon shown immediately before him on the pulpit receives his voice which is carried by wire to the transmitter set installed in the loft of the church. The wave length is 350 meters and the range is approximately 350 miles.



Photo, Gilliams Service

SEARCHLIGHT TO SWEEP THE GOLDEN GATE, SAN FRANCISCO, FROM MT. TAMALPAIS

b delays the interruption and carries on the current to some extent. This is remedied and the coil made much more effective by the condenser C; *a* being connected to one pole of the condenser and *b* to the other. When *b* separates from *a*, instead of the current endeavoring to cross the gap, it charges the condenser, and when contact is again made at *a*, the condenser is discharged along with the main current.

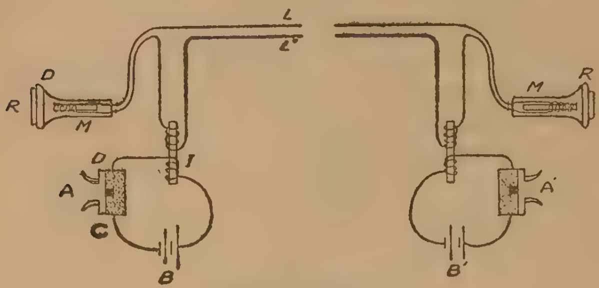
Induction coils are made capable of producing sparks more than three feet in length between the terminal points. If these are round balls a few inches in diameter instead of points, the spark is shorter but of very great energy. Its greatest service nowadays is in telephoning and to send out the waves of wireless telegraphy.

THE TELEPHONE

The telephone is essentially an application of induced currents. The details of central-station switchboards and connections are complicated, but the telephone action may be understood from the arrangement of a local battery circuit.

A transmitter and a receiver are required at every station. The transmitter A, on page 306, has a thin metal disk D, which makes contact with carbon granules C in the case back of it. This carbon packing is part of the circuit of a few local battery cells B, which circuit is also the primary of a small induction coil I. The receiver R contains a permanent magnet M (which may be straight or horseshoe in form), and is wound by the wire that forms the secondary of the coil I and the line LL′. Near the pole of M is a disk of iron D′, which is all the time under the attraction of M. The circuit of B is open until the

removal of R from its hook closes it. D is set in vibration by sounds at A; the vibrations cause varying pressure upon the carbon granules C; every little change of the pressure changes the resistance and strengthens or weakens the primary current from B; every such change increases or decreases or reverses the induced current in I and



THE TELEPHONE

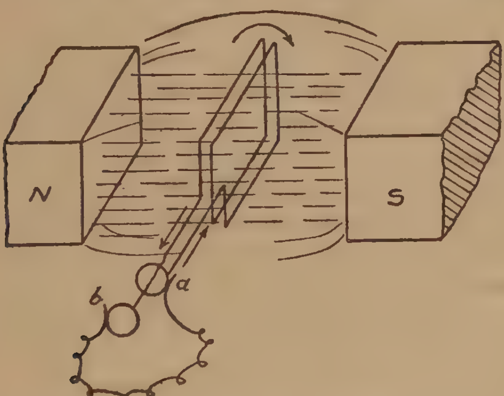
Local battery circuit

along the line L; every fluctuation of current in L varies the attraction of M in the receiver upon D'; the vibrations of the latter are repetitions of those of the transmitter D, so faithful that the speaker at A can be readily recognized at the distant receiver R by the tones of his voice. Nowadays the line is so connected up that service is supplied from the central instead of the local battery which used to be installed with each instrument.

THE DYNAMO AND THE MOTOR

One of the commonest and most effective ways to induce a current in a coil is to mount it upon a shaft between the poles of a powerful magnet and make it rotate rapidly. This is the basic principle upon which the electric dynamo acts. The rotating coil

is called the armature, and the magnets producing the field in which the armature rotates are the field magnets. One end of the coil leads to a metallic ring on the shaft against which presses a brush. To this is connected one terminal of the circuit that is external to the machine, and along which the electrical work is to be done, whatever it may be. The other end of the coil is similarly united to another ring. With every revolution of the coil a current is sent through it twice, alternating in direction, making what is known as an "alternating" current. When a current is wanted continually in



THE PRINCIPLE OF THE DYNAMO

Electromotive force induced in a coil by rotating it in a strong magnetic field

the same direction, or as it is called, a "direct" current, it is secured by causing the external current to reverse simultaneously with that in the coil. Instead of a ring on the shaft, each end of the coil is a single longitudinal bar of metal that is in contact with its brush only for a short time, or while the current in

the armature is not reversed. Before reaching the position of reversal (when the plane of the coil would be horizontal) each bar has broken its contact with the brush, and when the E. M. F. is reversed, the ends of the coil have exchanged their brush contacts, and the current is sent through the external circuit as before. The alternations still occur in the armature, but the current is not reversed outside; it is, however, interrupted. The bars thus effecting a change constitute a "commutator." By making the bars narrow, their contact with the brushes is brief, and they are so placed on the shaft as to be in contact when the coil is in its most effective position for generating E. M. F. One coil may be followed by another which is just coming into this best position as its predecessor is passing out, and through its commutator bars renews the current. As many of these successive coils may come into position as desired, and thus the current is made continuous though always somewhat pulsating in character. The magnetism of the field magnets is maintained by shunting a part of the current around iron uprights forming a yoke, making a huge electromagnet.

The dynamo is a machine for converting mechanical energy into electrical. The electric motor is a machine for converting electrical energy into mechanical. The reverse of the dynamo in purpose, its action is that of the dynamo reversed. If the current from an extraneous source is sent through the coil of a dynamo when the coil is in a position such that the magnetic lines of force between the field magnets are perpendicular to those called into play by the electric current in the coil, the latter is impelled to take a position in which its lines of force

are parallel to those of the magnetic field and it turns into that position. The effort upon it to cause it so to turn is its torque, and can be made greatest by having its brushes so placed as to be in contact with the commutator bars when the plane of the coil is in its proper position relatively to the magnetic field.

CHAPTER XXXVIII

HOW THE ELECTRIC CURRENT PRODUCES HEAT AND LIGHT

WHERE there is little resistance, little E. M. F. is required to send a current and little energy is expended, but to send a current, i. e., so much electricity per second, through a high resistance is like raising many pounds of mass many feet per second against gravity, and the work of transferring the electricity is the quantity multiplied by the potential difference; or, if the current in amperes is multiplied by the E. M. F. in volts, the product is the entire work of the circuit per second in joules. Work or energy is joules, but work per second is watts. If nothing else is accomplished by this current, the energy all goes to heat the conductor. If this is made white-hot it emits brilliant light, and it is by such means that the usual incandescent electric light is produced. The term is somewhat of a misnomer—a lamp of that kind is an electric lamp, but the light is not electric light except as to the means of heating the glowing filament. The light is precisely the same in character as if the material had been made white-hot in a furnace.

The arc light is produced by having an E. M. F. of thirty volts or more to drive a current through a conductor. If this is broken by a minute gap, at the instant of separation a high resistance arises between the two ends, great heat is suddenly con-

centrated there, the ends of the metal will be melted and even vaporized; if of carbon, they become white-hot and give off minute particles of incandescent carbon along with carbon vapor, bridging the gap with a gaseous mixture that is highly resistant, yet transmits a current. The ends may then be separated as far as an eighth to a quarter of an inch (still further with higher voltage), and the vapor joins the terminals in an arched form; hence the term "arc light." The heat is intense and the glow of the positive carbon dazzling.

We have learned that mechanical work has its equivalent in heat. If four able-bodied men worked steadily at what may be regarded a reasonable rate, they would produce something over one-half a horse-power, and if their labor were concentrated upon a bit of carbon and carbon vapor one-eighth of an inch in diameter and of equal length, it might be expected to raise the material to a very high temperature. It would just about keep one good arc light going, for such a light would use ten amperes of current at forty volts; that is an activity of four hundred watts, and 746 watts equals one horse-power. We do not often think, as we might do when we see such a light, of three or four men hard at work to produce and maintain it. Its energy would heat a pint of water from freezing to boiling every seven and a half minutes. If a man weighing 165 pounds climbed stairs two steps every second, he would be working at the rate of two-fifths of a horse-power, or 300 watts. It would be hard for him to keep that up long without resting, yet even such treadmill labor would not suffice to maintain the arc light just described. It would, however, maintain twelve good incandescent lights rated at 25 watts.

The electric arc provides the highest temperature we can produce artificially. It has been utilized as an "electric furnace," and has been applied especially to unite pieces of metal end to end in what is called "electric welding." The process really consists in forming an arc between the ends that are to be joined, raising them to a melting temperature, and thus fusing them together. It is successfully used to unite bars or tubes not only of iron, but of copper, brass, or other metals.

In commercial transactions it is not electricity that is paid for, but the energy it expends or the work it does. When supplied to users, no matter for what purpose, whether light, heat, or power, the user does not pay on the basis of the light or heat he obtains. The supply is metered by some contrivance that keeps account of the quantity per second multiplied by the potential difference at which it is delivered. This product is in watts, or in units a thousand times as large, called kilowatts. Whether it furnishes an acceptable supply of light or heat depends on the efficiency of the lamp or heater. Watts are work per second; if electrical energy is supplied at the rate of one watt, it is one joule per second; if kept up for a hour it would be called a watt hour, and would amount to 3,600 joules—equal to 864 calories, or 2,643 foot-pounds, and that is simple energy or work—that it is which is bought, sold, or bargained for.

CHAPTER XXXIX

WIRELESS TELEGRAPHY

IT was early discovered that the spark of a Leyden jar was not simply a single one-way discharge, but surged back and forth many times with exceeding rapidity. This oscillating spark sets up electric waves through the ether of space—but nothing came of this until some form of receiver or detector was invented, which responded to the vibrations or was in resonance with them. When this was found wireless telegraphy was achieved.

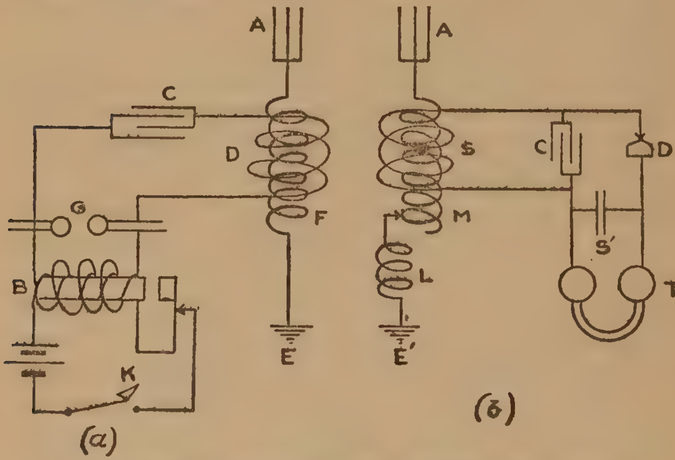
The spark from an induction coil is longest when its terminals are pointed, but if they are blunt, and are connected with the plates of a condenser, the quantity as well as the potential is large, the spark is shorter, the energy of discharge is concentrated, and at the same time may be very great; in contrast with a small spark between points, it is like the discharge of a monster cannon compared to that of a popgun. It gives rise to electric waves throughout space, which are continued so long as the coil is kept in operation by holding the key closed.

The refinements of the operations by which signals may be sent half round the world, and there received and translated, are beyond a simple and limited explanation, but a brief and concise view of wireless communication is here given. As with the telephone, special apparatus is required for sending

or transmitting signals, and also for receiving or detecting them.

In the diagram below (*a*) represents a typical arrangement at the station for transmitting and (*b*) that at the receiving station.

In sending, B is a high-tension transformer or induction coil which charges the condenser C on closing the key K. As in the induction coil, the



WIRELESS TRANSMITTING AND RECEIVING STATIONS

condenser is connected with the terminals at G, and discharges across this gap in a heavy spark of high-frequency oscillations. The conductor from C to G is wound around a coil at F. This coil is part of a line extending from the ground to a series of parallel wires suspended in the air and called an "antenna" or "aerial." The chargings and dischargings of C occur many times during the depression of the key, and the oscillations in D induce corresponding oscillations in the antenna, which sends out waves into space.

To perceive these waves at a receiving station requires an antenna associated with some form of "detector," usually of the crystal or the audion type. A telephone receiver is part of the detector circuit, by which the action of the electric waves on the detector can be heard, and the signals interpreted. To be effective, the receiving antenna circuit should be attuned to the wave length of the transmitting station with which it is working, and an equipment is so constructed as to be variable in this respect within a certain range. This is like the resonance considered in connection with sound, pages 225-235. The waves used in radio communication have lengths from 150 to 10,000 meters (one-tenth of a mile to six miles). In sending messages, the key is manipulated as in telegraphing, and the electric waves are sent broadcast in groups corresponding to dots and dashes.

When the waves from the aerial of the sending station impinge upon the receiving aerial AMLE′, page 314 (*b*), they set up an alternating E. M. F. which induces a high-frequency alternating current in the circuit SC. This has a coil at S wound around the antenna coil, like that at D in the sending station. But here, instead of the induction coil being connected with the condenser C, it is connected with a telephone T, through a detector D. This is either a delicate crystalline contact, or a special vacuum bulb which contains a grid of fine wire heated by a local circuit in front of a metal plate. This bulb is called an "audion" detector, and the gap of rarefied gas between the grid and the plate is sensitive to electric waves. Both of these detectors convert the alternating current into a pulsating one-way discharge, and thus make it effective in the telephone receiver. They

also have the effect of amplifying the sound. The action is assisted and controlled by a "stopping" condenser S′. The "tuning" of the receiving apparatus to resonance with the waves from the sending apparatus is done by moving the contact of the partial coil L along the other part M so as to adjust the capacity of the line from A to E′ to such a wave length as that of the incoming waves that reach the aerial A. This is very like adjusting the length of the resonant air column to the waves from the vibrating fork.

The invention has been extended so far that the variations of the outgoing waves may be produced by a telephone transmitter, and be received in like manner, bringing wireless telephone service closely in the wake of sending signals by a Morse code of dots and dashes.

CHAPTER XL

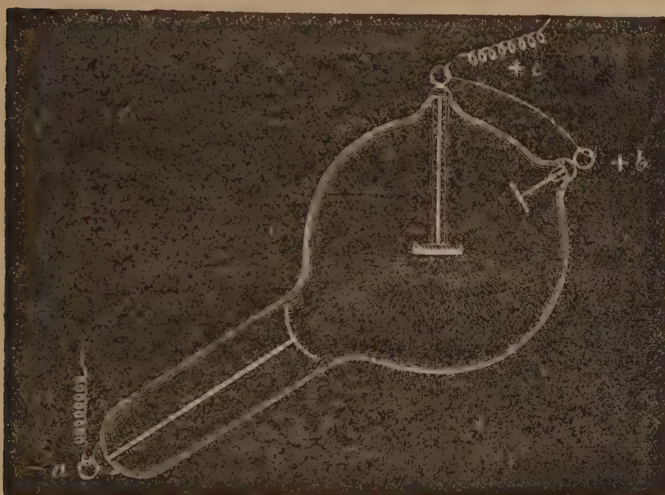
X-RAYS—CROOKES TUBES—CATHODE RAYS

NO more startling discovery in physics has ever been made than that of the X-rays, by Professor Röntgen, of Würzburg. A potential difference between the terminals of an induction coil or an electrostatic machine, that would be required to produce a spark one inch long in air at ordinary pressure, will break across a much wider gap if the pressure is reduced. By connecting the terminals of the machine with metal pieces that enter a vacuum bulb, the effects of the discharge can be studied in vacua of various degrees. The wires leading into or out of a bulb are called electrodes, the one connecting with the positive pole of the machine being the anode (the way to or into), and the negative the cathode (the way from or out of). A bulb from which the air has been nearly exhausted, or the pressure reduced to a millionth of an atmosphere is called a Crookes tube, from the English physicist and chemist, Professor William Crookes, who first employed such vacuum tubes in connection with electric discharges in high vacua. Here the number of molecules has become so diminished, that on the average they move farther without striking one another than the dimensions of the tube. When the ends of the induction coil are connected with the electrodes of the tube and the coil is set in operation, the discharge

that occurs when the current in the primary is broken is the most intense in its effect. The cathode within the tube discharges minute, negatively electrified particles, that are shot off at great speed in straight lines perpendicular to the surface of the electrode. These are cathode rays. If the cathode has a concave form, the streams of particles are concentrated in a focus. They have various interesting properties, but especially they are the exciting cause of X-rays. The negatively electrified particles are called electrons and have a speed of 30,000 to 100,000 miles per second, depending upon the potential difference between the electrodes. This is a velocity approximating that of light (186,000 miles per second), and here, for the first time we come into contact with quantities and conditions that bear upon the reaction of such particles upon one another.

When cathode rays impinge upon bodies of material such as metal or glass, they penetrate the bodies more or less, but also affect the molecules at the surface in such a manner that these, in turn, send out through the ether pulses of very high frequency, which traverse space in waves so short that the highest polish we can give to any surface of glass or metal is like a mass of coarse granules to these waves when they strike it. The waves cannot, therefore, be reflected or focused by a mirror, like ordinary light. They are capable of penetrating many substances that are impervious to ordinary light, organic substances particularly, and like cathode rays they cause fluorescence in glass and many minerals. The lines along which the waves advance are the X-rays, which were so named in the first place because of their novelty and unknown character.

In the X-ray diagram, the electrode *a* is connected with the negative terminal of the induction coil, and from the cup-shaped end of it proceed cathode rays, which come to a focus upon a plate of platinum; from this issue X-rays in all directions on the side of impact, so that the glass bulb on that side of the plate



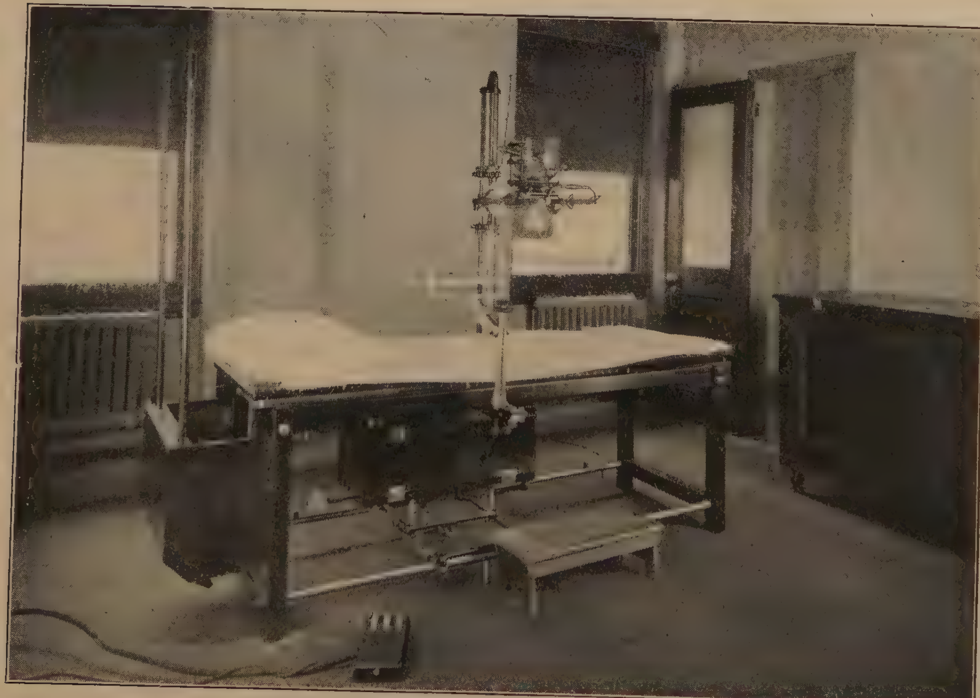
AN X-RAY TUBE

lights up with a rich green or blue color, while the other portion is dark or unexcited. If the glass is thin, the greater portion of the X-rays pass through it and can produce their own characteristic effects externally. It is this portion that reveals objects or produces photographic effects in applications of X-rays. The rays themselves are not visible either inside or outside of the tube. The green light of the tube is ordinary light of that color and may be extracted from sunlight or from various substances without the help of cathode rays or electrical excita-

tion. It is in this case, however, a result of the X-rays striking the glass. This lighting up under the X-rays is called fluorescence, further described in the chapter on Light.

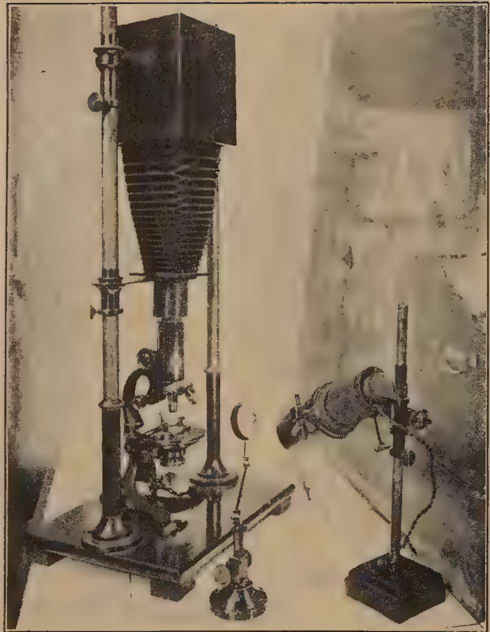
To view objects by means of X-rays a box, wholly dark within, has one end made of cardboard that is coated on the inside with a layer of fine mineral substance that is strongly fluorescent under these rays. Tungstate of calcium is one of the best and cheapest of such substances. If this end of the box is put in the path of the rays from the tube, and the observer looks into the other end, at the same time excluding all other light, the inner or mineral surface of the cardboard is luminous with a bluish-white glow, as the effect of the rays upon the crystals. This glow, again, is not the X-ray, but ordinary light emitted by the crystalline coating. Such a box is a "fluoroscope." If an object, as the hand, is placed against the outer side of the cardboard, it intercepts the X-rays in some measure, but not in all parts equally; the flesh offers little hindrance to the passage of the rays, and therefore does not greatly reduce the fluorescence of the screen behind it; the bones are more impervious, and more effectually cut off the rays, so that the screen behind them is nearly black. Thus the picture as a whole, shows the bones dark, in a hazy envelope of lighter tissue, upon a still brighter ground.

For photographing the plate is carefully wrapped in paper that completely excludes light, and then the figure to be photographed is placed upon or against this on the film side and the X-rays are directed against it. Where they penetrate to the sensitive film they darken it, just as light does; and where they are intercepted the plate is unaffected and re-



X-RAY ROOM IN A MODERN HOSPITAL

Photo, Fifth Avenue Hospital


Photo, A. N. Mirzaoff

APPARATUS FOR MAKING A MICRO-PHOTOGRAPH


Photo, A. N. Mirzaoff

STUDYING BULLETS UNDER A POWERFUL MICROSCOPE

mains light. When developed, the result is a negative, opaque parts of the subject appearing light and the transmitting portions dark, but not reversed in position as photographic negatives are. From these, positives are printed like ordinary photographs.

THE ELECTRON THEORY

As a result of the study of electric discharge in gases, the electron theory of electricity has been developed. In this the structure of the atom is so depicted and its behavior so described as to account for facts newly discovered, especially in connection with radioactive substances; and to be applied to the conduct of molecules in respect to temperature and gaseous pressure, in heat phenomena, and in matter generally.

CHAPTER XLI

LIGHT

HOW LIGHT SERVES US IN SEEING

LIGHT, in the sense in which it is usually understood, is the agent external to ourselves by means of which we see. In a scientific sense it is energy in the form of radiation, and radiant energy is very comprehensive, producing many of the effects ascribed to heat, and still many others that have nothing to do with either heat or seeing. Even that portion which affects our vision also carries with it the capability of producing chemical changes.

If we fail to see distinctly, this is due to one of two conditions: (a) inadequate light, giving poor illumination, or (b) a blurred and confused appearance of things, owing to a defective or disordered organ of vision. In any case seeing or failing to see is in obedience to laws of physics. For a remedy in the first case mentioned, the spectator seeks more light—if he is reading by light from a single source he instinctively moves up nearer to the source, and the pupil of the eye expands to admit more light into it. He can obtain no remedy for the second case until the nature of the defect is understood. But it is by means of light that he sees at all, and always his impression of what he sees is due to the light as it reaches him, and not necessarily as it is emitted from the object that is seen. This is true

with reference to position or direction as well as to shape or color.

The saying that "seeing is believing" implies that the sense of sight is not so readily deceived as the other senses, but light plays us many tricks, and optical illusions are probably as numerous and as varied as any other kind. It is not always wise offhand to pronounce an object "red" or "green" simply because it looks so. Take a flat bottle of petroleum (not refined) and view it directly, by sunlight coming through it it is a red-brown; look at it obliquely in the same light, it is bluish green. Pieces of glass all in white sunlight are red or blue or yellow, according to the light that comes from them to the eye. If anyone thinks he saw the sun setting, he saw it after it had set; if he thinks he saw it rise, he saw it before it reached the horizon. A straight stick makes a curious elbow where it dips into water. Into pellucid water, apparently not more than a foot deep, one may thrust his hand to pluck a bright object from the bottom, only to find that his arm is too short to reach it. Angles and distances have much to do with appearances; a pea looks as large as the moon if held near enough to the eye. Instances might be multiplied, and for some of these we shall presently find an explanation.

HOW LIGHT IS AFFECTED BY BODIES WHICH IT ENCOUNTERS

Light travels through space with a speed of 186,000 miles per second, the highest velocity of which we have any experimental knowledge, and a continuous line marking out the direction in which it progresses from point to point is a ray of light. When light falls upon bodies it is sometimes changed

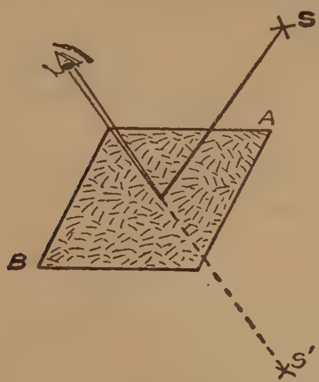
not only in direction, but apparently in its character. Gold leaf, exceedingly thin, is of a beautiful yellow or orange color, but if held between two pieces of clear glass and viewed by light coming through it, the color is rich blue or green. Some substances, like glass or water, are very clear; a screen of such material interposed between the eye and an object does not prevent the latter from being seen distinctly; these are called "transparent" substances—they can be seen through. Another class completely intercepts the light; they are "opaque," though there are few, if any, substances that are wholly opaque if made very thin.

Between these two classes of substances, the transparent and the opaque, are many kinds of bodies which permit light to pass through them with more or less freedom, but so restricted or altered in character that it does not properly indicate the position or nature of the object from which the light proceeds. These are called "translucent"; they permit light to pass through in some measure, but cannot be seen through.

Light falling upon a body, then, is either reflected from it, or transmitted through it, or absorbed by it. The total light may be disposed of partly in each of these three ways.

The direction of a ray of light is always altered by reflection. If light from a source S, as illustrated, falls upon a nonluminous body (i. e., one that does not emit light of itself), which is not highly polished, the light is scattered in all directions, very little of it is reflected directly to the eye, and S is dimly perceived or not at all. Every part of the surface AB becomes, as it were, an independent source of light on its own account, and is seen as

such, the total of all the points constituting the surface of the figure. But if the light is only partly broken up, that portion that is directly reflected to the eye makes S visible. With a moderate polish the surface is readily seen and also S; with a higher polish the surface becomes less distinct and S



AN OBJECT THAT IS NONLUMINOUS IS SEEN BY SCATTERED REFLECTION

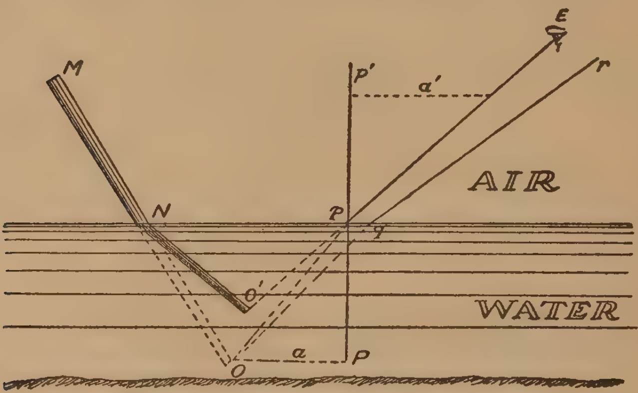
becomes more brilliant; if the polish of the surface is very perfect it becomes invisible. The light of S then reaching the eye is said to be "regularly" reflected, and if AB is a plane surface, S will be seen at S′, as far behind AB as S is in front of it.

The velocity of light is different in different media, and when it passes from one medium, as air, into another, as water, or the reverse, if it meets the common surface of the two media in any direction other than perpendicular to this surface, its direction of progress is altered. Such a change is called "refraction." It causes many apparent distortions and displacements.

Still another change of direction occurs when light passes the edge or border of an object. This is "diffraction."

THE KINK IN A STRAIGHT STICK

If MNO, in the figure below, is a straight stick dipping into water, to an eye at E it appears to make a sharp angle at N and to take the position MNO′. Every point of the stick, both above the water and



THE FAMILIAR KINK IN A STRAIGHT STICK

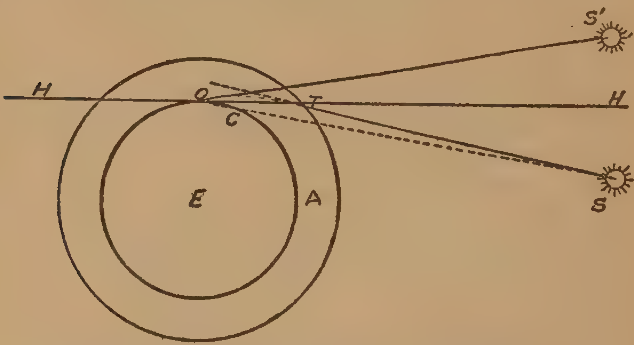
beneath it, is seen by light coming from the point to the eye; but if a line of light is proceeding from O directly toward E, as O*q*E, when it emerges from the water into the air at *q*, it is refracted, taking the direction *qr*, and misses the eye. There is some ray as O*p* which, after refraction, enters the eye in the direction *p*E, and tracing back along this line E*p*, the eye sees O at O′. Other points of the stick between N and O are seen along NO′; in the air the part MN is seen in its true position, but the whole rod has the apparent position MNO′. Light from O reaches E along the path O*p*E, being bent or re-

fracted away from the perpendicular P′pP at p in passing from water into air. If a ray from E reached p, it would enter the water in the direction pO, or be deflected toward the perpendicular. At equal distances from p on the ray, in the air and in the water, measure the distance of the ray from the perpendicular, as a in the water, and a' in the air. No matter what ray of light is considered, as OpE, or any other ray that might be drawn for the same two media, as water and air, these perpendicular distances a and a' will have the same proportion. For light passing from water into air, a is 3/4 of a'; from air into water, a' is 4/3 of a. From air into common glass it is 3/2. What this ratio really signifies is the relative velocity with which light travels in the two substances—3/4 as fast in water as in air; 2/3 as fast in glass as in air. If the eye looks vertically down upon an object below the surface of the water, the object appears to be nearer the surface than it is in reality; if the bed of the stream or pond is visible, the water appears to be only three-fourths as deep as it actually is.

In the sun diagram, page 328, E represents the globe of the earth, and A is the shell of atmosphere around it. HH is the plane of the horizon to an observer at O. If the sun, S, is below HH, its light will be cut off from O by the earth at C, and the sun cannot be seen if its light goes straight from S to O. Also a straight ray from S in the direction ST would not reach O, but would pass above it. At T, where the ray reaches the atmosphere, it is bent downward, and steadily curves downward in passing through the denser and denser atmosphere, reaching O in the direction S′O; and to the observer the sun appears at S′ above the horizon, while its actual

position is below it. This occurs both at sunrise and sunset, and in fact the sun always appears out of its real position, except when it is directly over head, which it never is to anyone in latitude more than $23\frac{1}{2}°$ north or south.

Every one has seen the glare and quiver of air over a hot road in midsummer; something of the

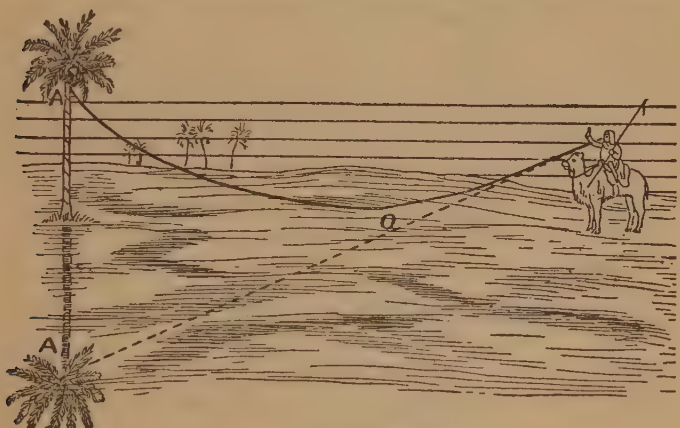


THE SUN VISIBLE THOUGH BELOW THE HORIZON

same sort may be seen above a hot stove plate. The heated air rises above the burning sands and glistens along the surface of the desert. The sight of a tree in the distance inspires hope in the traveler, tortured by thirst, if only for the relief of its shade; but better than that, he sees the tree reflected, as he thinks, in a pool of life-giving water. It is only a mirage.

In explaining this illusion it must be kept in mind that we see things by the light that comes to us from them, and that the light, after undergoing changes both in character and direction, may give us a false idea of the object both as to appearance and position. In the preceding illustration, the rays from the sun, entering the atmosphere where it is rare, are bent downward, and more and more as the

air becomes denser. Now just above a hot surface the air may be rarer than it is at a higher level. Light from a higher point, as the tree in the mirage, coming obliquely down into strata of air that are successively rarer, will be bent in exactly the opposite way from that in the displacement of the position of the sun. At some point, as O, it is reflected at an angle, such that in its onward course it enters the eye of the observer in a rising direction, and to him the scene above the earth appears inverted, the shimmering air seeming the surface of a pool in which the landscape is reflected. This is one of the simplest of atmospheric illusions; varying density



THE MIRAGE

Why the traveler in the desert believes he is approaching an oasis

of the air in strata both above and below the level of the eye produces many perplexing appearances of distant objects.

We see then, that under various circumstances, the direction in which light progresses may be changed —it may be even reversed—and the ray may be a

straight, a broken, or a curved line. The statement that light travels in straight lines must not, therefore, be taken as correct, unless the proper conditions are understood. In the illustrations of the sun below the horizon, of the mirage, of the bent stick in the water, the light from the object in sight was deflected from a direct course, either continuously or abruptly, and the fact that it may be so deflected by reflection or refraction, provides us with practically all the means we have of turning light to account with optical instruments; for nearly all these employ mirrors or lenses, which is the same as to say "make use of reflection and refraction."

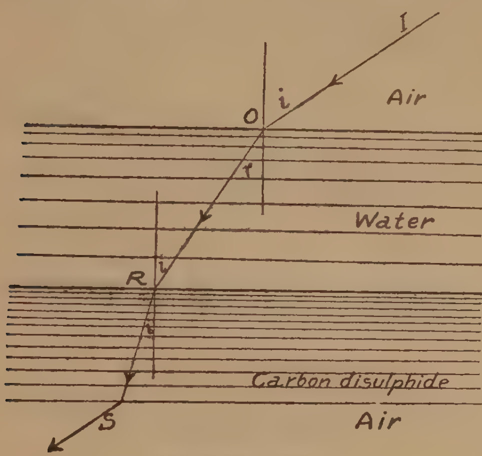
And yet, fundamentally and normally, light does proceed in straight lines. If that were not the fact we should consider a deviation from it as irregular. What, then, is the condition under which a ray of light is straight? Simply that the medium through which the light is traveling—air, or water, or glass—whatever it may be, shall be homogeneous, i. e., uniform in its constitution, especially its density and its molecular structure. As the air is denser at some places than at others, it is a medium in which light may take a curved course; a piece of glass may have little or no difference in density, but if it is put into a strained condition by bending or compression, its molecular structure will be altered and light will be deviated from a straight path in passing through it.

Usually the air within such distance as our observation requires does not vary appreciably in character, and the course of light through it is unaltered.

The change of direction by regular reflection follows the simple law that the ray leaves the reflecting surface at an angle equal to that at which it strikes

it, but on the opposite side of a line perpendicular to the surface; the line before reflection is the "incident" ray; that after, the "reflected" ray; and the angles they make with the perpendicular are angles of incidence and reflection, respectively.

In refraction, as we have seen, the change of direction may go on steadily with the advance of the



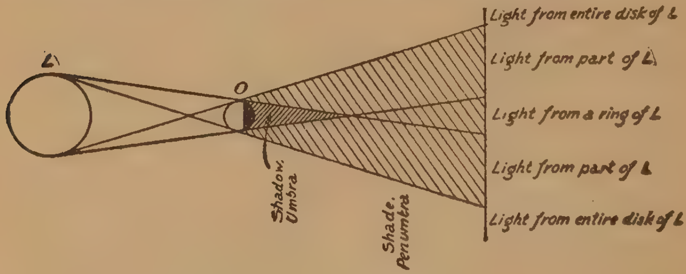
DIFFERENT MEDIA

Light through air, water, carbon disulphide

light, but it is usually most marked when the light passes from one medium into another. It may be moving in a perfectly straight path in, say air, and coming obliquely to the smooth surface of water, as IO in the figure above, it is bent toward the perpendicular, and proceeds along OR. This refracted path will again be straight so long as it continues in a fluid of the same character, but if the water rested upon, say carbon disulphide, the ray arriving at R would again be bent, taking the course RS in the lower liquid.

SHARP SHADOWS RESULT FROM STRAIGHT RAYS OF LIGHT

Sharp and distinct shadows could result only from light traveling in straight lines, and when it does so result, the shadows are of definite geometrical form. When an opaque object is lighted by a body larger than itself, it cuts off the light completely from a tapering region behind it, and partially from a



SHADOW AND PENUMBRA

Light and shade from a luminous body, *L*, larger than the object, *O*, on which it shines

widening region, as shown in the diagram of the shadow and penumbra. The first of these is the complete shadow or umbra; the other is a partial shadow or penumbra. The next figure shows an interesting effect of light and shade from diffused light. It is a familiar appearance of a doubled window screen, not exposed to direct sunlight, and when viewed obliquely in a room that is not strongly lighted. Each piece of wire gauze is irregularly warped and twisted, so that the distance between the screens is very unequal, and the view through one screen is interrupted by the other in a fantastic fashion. The whole surface is covered by a pattern of shadows

LIGHT AND SHADE PRODUCED BY WARPED SCREENS

and half shadows that shift in position and change in shape with any movement of the eye or of the screen.

LIGHT IS INVISIBLE

It is well to note before going further, and to keep in mind, that although light is a revealer, it is not itself a thing that can be seen—it is invisible. One

cannot see light or tell what it looks like. Long after the sun has sunk below the horizon, and we have passed completely into the shadow of the earth and are enveloped in darkness, the sun's light is streaming above us and beyond us into the firmament, and if it were at all visible it would be plainly seen. Every star in the heavens is a sun, sending its beams throughout space, yet the regions between the stars are black. On a clear moonless night, excepting those glowing points, the universe is dark, though flooded with light.

CHAPTER XLII

MIRRORS AND LENSES—THE CAMERA

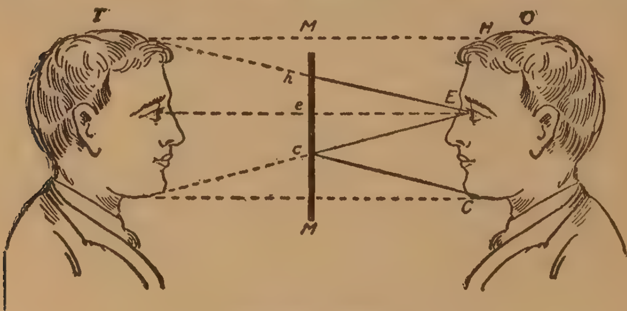
IMAGES FORMED BY REFLECTION

WHEN rays of light are brought together in one point, that point is a focus. If rays diverging from any point are made to come together again in another point, the second point is called the image of the first; a limited portion of a body may have the light from its many points reassembled in points spread over a larger or smaller area, and the image may thus be larger or smaller than the object. When the rays are so modified or redistributed as actually to meet in one spot, this is a "real" focus and the image a "real" image; but the rays might be so shifted or modified as to be separating, proceeding and appearing as if they actually came from a common point where they never had been at all; this point is a "virtual" focus, and the image of the object emitting the rays is a "virtual" image, but not a real one. It may be perfectly plain to the view, but a phantom nevertheless.

That is the kind of image one sees in a looking-glass. If MM, as here figured, is a plane mirror, O a face in front of it, and I the image, the latter appears directly behind the mirror, as far back as the object is in front. If the light from the chin C is to enter the eye, it is plain that it will be reflected from *c*, just half as far below the line E*e* as the vertical distance from E to C. If light from the hair

H is to enter E it is reflected from h, half as far below H as E is; and in general, to see a figure of any given size the mirror must be at least half as large as the object; a man six feet tall must have a mirror at least three feet high to see his entire figure in it.

A curved mirror will produce a distorted image that may be enlarged or reduced in size compared with the object, and may serve useful purposes. Such mirrors are often used for amusement, by producing images that are grotesquely distorted. A long, slender person may be made to look ridiculously short and wide, while a stout one with beaming face is made to appear absurdly narrow with a pinched countenance. The cylindrical mirror MM shows how the object AB appears as ab after reflection, correct in length but much reduced in breadth. Any reflected ray R makes an angle with the perpendicu-



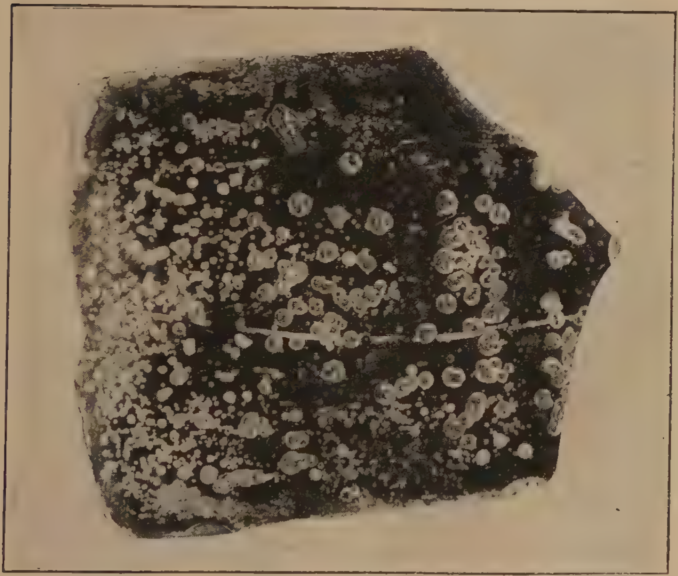
VIRTUAL IMAGE

A face seen in a looking-glass

lar p, equal to that made by the incident ray I, and appears to come from the image behind the mirror. If the cylindrical mirror were placed with its axis horizontal instead of vertical, AB would appear shortened instead of narrowed by reflection from it.

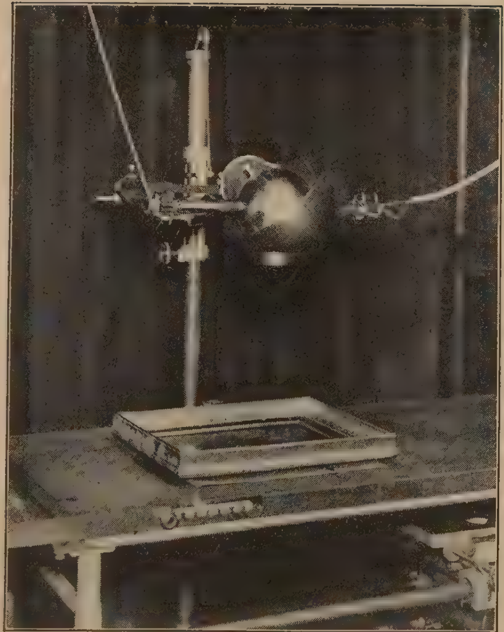
Photo, A. N. Mirzaoff

MICROPHOTOGRAPH OF LIVING LICHENS ON GLASS



Photo, A. N. Mirzaoff

MICROPHOTOGRAPH SHOWING DESTRUCTION OF STAINED GLASS IN FRANCE BY TINY LICHENS



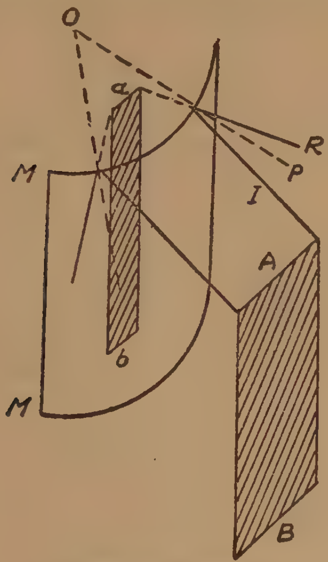
Photo, A. N. Mirzaoff

MAKING A RADIOGRAPH OF A PAINTING TO DETERMINE IF IT IS A GENUINE "OLD MASTER"

Photo, A. N. Mirzaoff

MICROPHOTOGRAPH OF MARKS LEFT BY A BULLET IN PASSING THROUGH MATERIAL—USED IN A TRIAL

The reflection of the sky, of clouds, trees, even one's own form and features, from the surface of still water, was an example of mirrors that was familiar to man in his primitive state, on a scale far exceeding anything that he has been able to produce



DISTORTED IMAGE

Reflection from a curved mirror

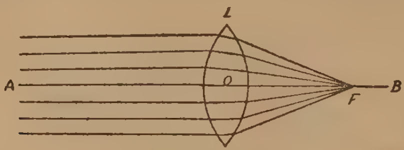
artificially, and when this reflector was followed by such polished surfaces as he could give to metals, mirrors came into familiar use long before any means of deflecting and of directing light by refraction was available.

LENSES; IMAGES FORMED BY REFRACTION

With the manufacture of glass, and an acquaintance with its effect upon light passing through it, came the production of lenses, by which rays of light

might be converged to a focus, or made parallel, or divergent at will.

A lens is a figure of some transparent substance, usually glass, with curved surfaces; it is, therefore, thinner at the edges than at the center, or the contrary. Light passing through it is refracted toward



LIGHT FOCUS

Rays and focus of light through a converging lens

the thicker portion. A lens thickest in the middle is called a convex lens, and light passing through it is made convergent or less divergent.

In the diagram above, L is a section through a double convex lens, i. e., convex on both sides, which is probably the most common form in use. The line AB through its center is its principal axis, and any other straight line through O is a secondary axis. Rays parallel to AB converge to a point F, called the *principal focus*, and all rays from F to L are parallel after passing through the lens. Rays from any very distant object are treated as parallel. In the diagram on next page, from a point P, beyond F, rays to L come to a focus on the principal axis at P′, which is the image of P. Rays from Q focus at Q′ on the secondary axis QOQ′ and from R at R′, and Q′R′ is a real image of QR. It is inverted, and in this case larger than QR. If the distance OP were twice OF, the image Q′R′ would be of the same size as QR, and at the same distance from O. The object and its image are interchangeable; either may be

regarded as the image of the other, and rays from a point on one come to a focus on the other. Usually, in determining sizes and distances, the thickness of the lens is supposed to be so small in comparison with the other distances concerned as to be negligible. From the triangles QOR and Q′OR′ it is plain that the relative size of the object and the image is just in the same proportion as their distance from the lens.

With a double concave lens, as in the figure on page 340, rays from a point, as Q, are more divergent after passing through L, and therefore do not again meet, but proceed as if they had come from Q′, which is therefore a virtual image of Q; similarly R′ is a virtual image of R, and Q′R′ of QR.

Lenses are combined in various ways to increase their power or to correct distortions or colors that arise from refraction through different portions of the lens. To form an image with a lens by means of light actually falling upon a point, then, requires a

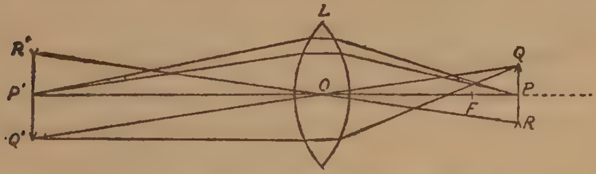
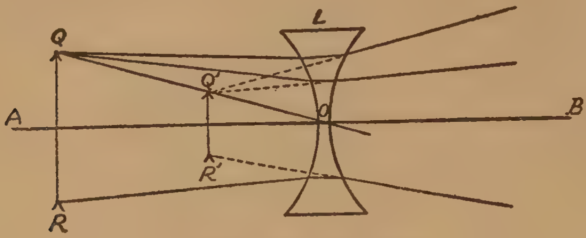


IMAGE FORMED BY CONVEX LENS

converging lens, though the image may be either larger or smaller than the object. The lens of a camera can be so adjusted in position as to focus upon a film at the back of the camera the image of objects in front of it, and as the light actually does fall upon the sensitive plate or film at the back, it acts chemically upon the film, which is impregnated

with some salt of silver, so as to darken it in proportion to the intensity of the light in the picture. This, when properly developed and fixed, is a photographic negative, being black where the original was light, and conversely. If, now, light is passed through the



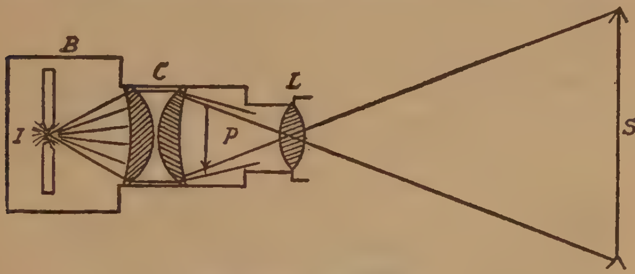
DOUBLE CONCAVE LENS

A concave lens produces a virtual image

negative upon another sensitive film, the latter will show light and dark as in the original scene. This is a positive, and is the picture that is ordinarily desired. So sensitive are the films that a minute fraction of a second is long enough exposure to a strongly illuminated scene to reproduce it in all its variations of light and shade. If the object is farther from the lens than twice its focal length, the picture will be smaller than the natural size, but by placing the object nearer, the image becomes larger, and when it is near the focal distance the image becomes very large and so far from the lens as to require some special extension bellows for the camera or some special mounting of the film to receive the image; the apparatus then becomes an enlarging camera.

From a negative is made a positive of the desired size for projection in the lantern, the standard being about two and three-quarter inches by three inches.

To exhibit this upon the screen, the box B, of the magic lantern, has a strong light at I and a converging lens at L. The lantern slide is placed at P, where it is illuminated by I, and its image is projected on the screen at S. The picture is brought into focus by moving L in or out to vary its distance from P. The light upon the small area on the lantern slide P is spread over a surface thirty or forty times as long and wide, and therefore a thousand or more times as great in area, and consequently the illumination of the lantern slide must be very strong if the picture on the screen is to be at all brilliant. To bring as much light as possible upon P, a strongly converging lens C (usually made in two parts) is placed near I. This is called a condenser. It collects a large cone of light which it converges upon P. The latter is so placed as to receive practically all the light from C, and it is therefore a brilliantly luminous object. When focused



THE MAGIC LANTERN

The camera reversed becomes a stereopticon or magic lantern

upon the screen it is enlarged and reversed in position. While the photographic camera has become a *vade mecum* with every traveler, this reversed use of it has been the means of exhibiting its work to large bodies of spectators.

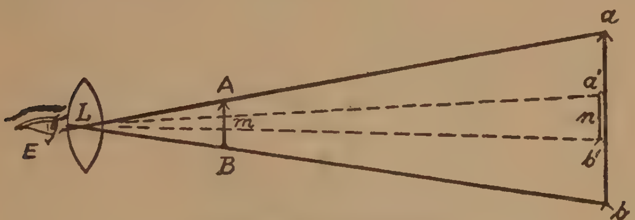
In addition to this the enlarging lantern has been applied to commercial uses. Artists and designers for large decorative and ornamental work, or display posters, prepare their designs on comparatively small sheets, with all the detail of lines that may be needed. These are photographed to a proper size for projection with an enlarging lantern. Against the side of a dark room large sheets or strips of photographic printing paper are spread out to such size as the design is to cover finally; sometimes twelve or fifteen feet in length or breadth. The picture is focused upon it, and after suitable exposure it is developed and fixed, and the design is thus accurately copied in its final size, in black and white. This is colored if need be, and thus designs for large mural decorations for walls or ceilings, for decorative panels, and notably for stained glass windows, are prepared in their true proportions, from which the artisan can go on with the work. In preparing a stained glass window, the large print can be cut up into pieces along the boundary lines of the colored parts, and these pieces are templets from which to cut out the glass; all this, when assembled, forms the window in its proper size.

DISTINCT VISION; APPARENT SIZE OF AN OBJECT

The eye has a large power of adapting itself so as to see distinctly objects at various distances, but for every eye there is some distance for which it requires no adaptation, and which is regarded as the distance of most distinct vision for that eye. This distance varies with different individuals, but it is normally from ten to twelve inches, and for convenience has generally been taken as ten inches or twenty-five centimeters. The apparent size of an object is

determined by the angle that is made at the eye by lines from the extreme parts of the object. If the angle is increased by viewing the object or its image at a distance of ten inches, this is magnified. An instrument which makes small objects look large is a microscope; one which brings into near view distant objects is a telescope; both are magnifiers.

The eye utilizes only the light that enters the pupil —an opening which is only from one-eighth to one-fourth of an inch in diameter. A large lens receives

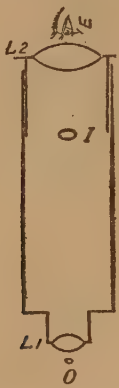


THE SIMPLE MICROSCOPE

more light upon it than does the pupil of the eye, but if it is a converging lens the rays from a large surface may be gathered into an area smaller even than this.

If the observer's eye is placed close to the simple convex lens L, called a magnifying glass, to view a small object AB (a letter of fine print, for example), this will be most distinctly in view if its distance from L (or, what may be taken as the same, from E) is a very little less than the focal length of the lens. It is distinct to the view because the rays from it seem to the eye to proceed from the distance of most distinct vision; i. e., ten inches, or AB appears as *ab*, ten inches from L. If AB were viewed without the lens L it should be placed at the same

distance, or in the position of a′b′. The angle at the eye formed by *ab* is *a*L*b*, which is the same as ALB; that formed without the aid of the lens is a′Lb′. This angle compared to ALB is practically the same as the distance L*n* to L*m*, or as ten inches to the focal



COMPOUND MICROSCOPE

length of L. If the latter were two inches, the lens would magnify five times. A lens so used is a "simple microscope."

If a lens L, figure above, of very short focus, is placed near a minute object O which is strongly illuminated, it forms at its conjugate focus a real image which is larger than O in the proportion to the distance IL_1 to OL_1. If I now is viewed through an eyepiece L_2 precisely as AB in the preceding figure was viewed through L, this image again is magnified. If I is twenty times as large as O, and is itself magnified five times by L_2, the view to the eye is one hundred times as large as O. With lenses of various powers at L_1 and L_2, various degrees of magnification may be produced. Such a combination of lenses is a "compound microscope."

A telescope consists of an object glass, or objective, which is a large lens to collect light and form an image of a distant object, and an eyepiece to magnify this image. The image is inverted, and if not reversed by another (erecting) lens, the object will appear inverted when viewed through such an eyepiece as we have described. The longer the focal length of the objective, the larger is the image it forms.

Suppose AB, telescope diagram, is the object, L the object glass and *ab* the image. This will be practically at the principal focal distance of L from the lens. If this could be viewed directly by the eye at a distance of ten inches, as in the figure, its apparent size would be the angle *a*E*b*; the angle formed at E by the object AB at a great distance is virtually the same as if E were at L, or it is the angle ALB, and this is equal to *a*L*b*. The angle *a*L*b* then, measures the apparent size of AB, and the angle *a*E*b* that of the image *ab*; these angles, in size, are just in the proportion which the distance from L to *ab* bears to

THE TELESCOPE

that from E to *ab*, or in the ratio of the focal length of L to ten inches. In a large telescope L may be a foot or more in diameter, with a focal length of forty feet or more. With this focal length its magnification is 40 feet divided by 10 inches, or 48 times. Now if *ab*, instead of being viewed directly by the eye, is viewed through an eyepiece, as in the case

of the microscope, the image *ab* is again magnified. If the focal length of the eye lens is two inches, it magnifies the image five times, and the telescope as a whole gives an apparent size of 5 times 48, or 240 times the apparent size of AB, and the object seen through the telescope appears in size as it would to the naked eye if it were only 1/240 as far away. That is what is meant by saying the telescope brings an object nearer.

A small amount of light from the object has to do duty when spread out over a correspondingly larger field of view, and on that account the magnification that can be used is limited. For the microscope strong artificial illumination of the object is employed, and with the telescope, to collect as much light as possible, the object glass has been made as large as mechanical skill in construction and perfection of material for the objective will permit.

The great telescope of the Yerkes Observatory has an object glass forty inches in diameter, with a focal length of sixty-two feet. The magnification from this is, therefore, 74+ times. It may be used with an eyepiece magnifying 40 times, making the total magnification nearly 3,000. If the light were sufficient to apply this to the moon, only a small portion of the disk would be in the field of view at one time, but any object would be revealed which the naked eye could distinguish at a distance of eighty miles. Mountains, valleys, large lakes (if there were any), would be distinguishable.

MOTION PICTURES

The ring of light that is formed by the glowing end of a stick as it is twirled around is familiar to everyone. It is an example of "persistence of vision."

The sensation of sight is due to stimulation of the optic nerve, which forms a network, the retina, upon the back of the eyeball, and when any portion of the retina is excited the effect does not cease immediately upon the cessation of the cause—it persists, sometimes as long as a tenth of a second before it quite dies out. There are few persons, if any, with whom the sensation does not last as long as one-twentieth of a second, and one-sixteenth has been generally taken as an average value. When an action or a movement does not occupy longer than one-sixteenth of a second, if it is all in the field of vision, the beginning of it will still be seen while the end of it is occurring, and the whole path is seen as a continuous line like the ring of fire or the much larger streak of lightning.

It is upon this principle that motion pictures are produced. Instantaneous views of a moving scene may be made to follow one another so rapidly that a second one may appear before the image of the first has faded out, and the eye sees one change into the other. A horseman standing upon the ground places his foot in the stirrup, rises into the saddle and gallops away. The performance is photographed and the pictures are exhibited, showing the action just as it occurred.

In taking a motion picture a narrow sensitive film in a long strip is unwound from one reel and wound upon another, passing across the field of the camera lens, stopping only for an instant to receive the image projected upon it when a shutter behind the lens is opened. This closes and opens in rapid succession, and thus pictures of the moving scene succeed one another on the film at the rate of as many as sixteen in a second. When this long strip is developed with

its hundreds of pictures, a positive is printed from it, and when this in turn is moved similarly behind the lens of a projecting lantern, the rapidly succeeding pictures on the screen enable the eye to reconstruct the original scene with the startling vividness that has made the "movies" an irresistible attraction.

Besides furnishing unlimited entertainment, the method has been used to show in a short time the progress of changes that may have been much too slow to be perceived as they were actually occurring. The growth of a plant or the opening of a flower which may have occupied days in its occurrence is photographed at intervals of perhaps every quarter of an hour; the difference in appearance of two such successive pictures will hardly be perceptible, though the whole series comprises the complete change of a bud into a full-blown flower. When exhibited in the kinetoscope or kinematoscope (as the motion-picture lantern is called), the whole succession of changes is displayed in a few minutes, and the process of growth is so speeded up that it can be actually seen in action.

There is promise of even greater advance of knowledge by applying the principle along the opposite direction. Means have been devised by which pictures may be taken with great rapidity. If 160 per second are taken upon a film that is jerked across the field of the lens ten feet per second, there will be ten pictures in every sixteenth of a second instead of one picture as in the ordinary film. If this film is put through the projecting lantern at a speed to show only one picture every sixteenth of a second, it will go only one-tenth as fast as it went when the pictures were taken, and, therefore, will occupy ten times as long from one view to the next as was occupied in

the action itself. The movement is slowed down, and yet is rapid enough to appear continuous. As a consequence, movements that it would be impossible for the observer to distinguish on account of their rapidity now appear to him quite deliberate, and he can trace them out and study them in detail.

The picture may, however, give an absolutely false impression. Anyone who has watched the movement of an automobile as it came to a stop or as it started into action in a motion picture must have seen, at some instant, the wheels turning backward while the car moved on forward. At one flash the spokes of a wheel are seen in a definite position; if, with the next flash from the projecting lantern a second spoke is seen just behind where its predecessor had been seen, and then spoke number three is seen just behind where number two was, the wheel will appear to be turning backward. Any moving object may thus be out of step with the rate at which the views are exposed, and though moving uniformly, may apparently be going ahead, or back, or standing still. If it is itself increasing or decreasing in speed, there is certain to be some moment when the exhibition is thus at fault, but it is for so short a time that it escapes attention.

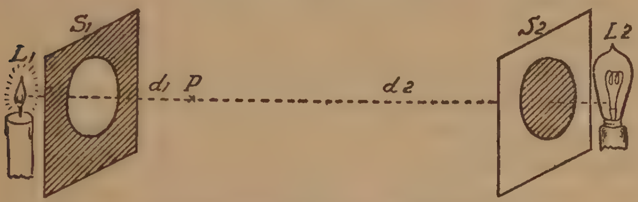
CHAPTER XLIII

THE MEASUREMENT OF LIGHT

THE illumination of any surface is measured by the amount of light upon a unit of area, say a square foot. Light emitted from any point spreads out around the point in every direction, and if the medium surrounding the source of light is uniform in its structure, a spherical shell around the point as its center is equally illuminated over its entire surface. If the shell is one foot from the light it will have a certain degree of illumination; if its radius is two feet its area is four times as great and the light per unit area, or its illumination is only one-fourth as strong; at three times the distance, one-ninth as great—the illumination decreases as the square of the distance increases. At any given distance, if the light is doubled or trebled the illumination is increased in the same proportion. With any light, then, at any distance, the illumination is determined by the intensity of the source of light divided by the square of the distance from it.

If a screen of soft but opaque white paper has an oiled spot upon it, that spot becomes translucent or lets some light through it. In the figure herewith S_1 is such a screen near the light L_1. On the side of S_1 next to L_1 the paper is white and as the spot lets light pass through it, it is comparatively dark; viewed on the other side, the opaque paper is relatively dark and the spot, by reason of the light com-

ing through it, is bright; this contrast in the appearance of the two sides of S_1 is easily noticed even in the presence of another light L_2 if this is at a considerable distance, say eight or ten feet from L_1. On moving the screen to the position S_2, near to L_2, the contrast is again seen, but now the spot is dark on the right side and bright on the left. Somewhere along the line L_1 L_2, as at P, the illumination is equal on



THE GREASE SPOT PHOTOMETER

In which the intensity of two lights is compared

both sides of the screen, and either the spot disappears, or it looks alike from both sides. If the screen is shifted from P a very little way to the right or left, the spot changes from dark to bright or the reverse. Call the distance to P from L_1, d_1; and from L_2, d_2; if L_1 and L_2 represent the intensity of the two lights, the illumination at P from L_1 is L_1 divided by d_1 squared; and from L_2 it is L_2 divided by d_2 squared; and as these quotients at P are equal, L_1 has the same proportion to L_2 as d_1 squared has to d_2 squared. If d_1 is 2 feet and d_2 is 8 feet, L_1 is to L_2 as 4 is to 64, or L_2 is 16 times L_1. By using a standard candle for L_1, the candlepower of any other light at L_2 is thus determined.

Great Britain, France, and the United States have adopted a common unit of light intensity, termed the International Standard Candle, and the illumination it gives to a square foot of surface at a distance of

one foot is called a foot candle. The unit for the quantity of light emitted is called a *lumen;* and the standard candle emits about ten lumens. An electric incandescent tungsten lamp rated at 25 watts has about 16 candlepower, or uses about one and a half watts per candle. An arc light is more efficient and more powerful, but cannot be used as a small unit. To maintain an arc at all would require about 90 watts, and this would give probably 200 candlepower. One using five amperes at 80 volts takes 400 watts and may have an intensity of 1,000 c.p., which is 0.4 watt per candle; but where a powerful light is needed, the extraordinary intensity that can be obtained by such a lamp more than offsets any disadvantages it may have. Placed slightly nearer to a mirror than the principal focus it throws a gradually widening column of light for miles and is known as a searchlight. A battery of such lamps on the United States ships of war before Santiago sufficed to keep the mouth of the harbor in such a glare of light on the darkest night that the Spanish fleet blockaded there could have no cover of darkness to aid them to escape; and the same means was in continual use by the fleets of the Allies during the World War.

CHAPTER XLIV

THE NATURE OF LIGHT

THERE is no wholly satisfactory theory as to the nature of light. The generally approved idea is that it is a motion of vibration in the ether of space. It travels, then, as a succession of waves, and it is now thought that these waves are excited by electromagnetic action. Whatever may be the ultimate explanation, the wave theory accounts better than any other for many phenomena of light. The waves of light result from a motion transverse to the direction of progress, instead of longitudinal motion, as in sound. They are like the waves in a rope that is shaken at one end by the hand; but in a line of light, usually the transverse motion is across the path *in any direction,* right and left, or up and down, or obliquely. Still, any such vibratory movement can be regarded as made up of motion partly in each of two directions, say vertical and horizontal.

WHAT IS POLARIZED LIGHT?

An analogy with material things may be of help. We may imagine a swarm of insects advancing as a body, while individually flying in every direction across the path of their progress. They encounter a screen which bars their advance except through a narrow vertical slit; if they cannot reduce their movement to a vertical plane they cannot pass through; they can only pass while moving up and

down. Instead of one slit there might be many such, parallel, constituting a grating; these slits might be extended beyond the screen as narrow crevices between walls, and any transverse movement would be impossible except up and down. When action of any kind is constrained so as to be limited or fixed in direction it is said to be "polarized." Those insects whose flight has no horizontal element in it crosswise to the line of advance can go forward; if, now, these meet with another barrier containing narrow openings or slits that are *horizontal,* they cannot pass and their further progress is completely cut off.

Some crystals are of such structure as to form walls of molecules with crevices between them, and light passing through them is polarized. Also light is polarized when it is reflected from a nonmetallic surface at a certain angle of incidence which varies with different substances. A crystal of calcite (Iceland spar), when cut in a particular way, is a standard form of apparatus for producing or detecting polarized light. It is known as a Nicol prism. If a beam of ordinary light falls upon a crystal of tourmaline, that which passes through is polarized. If it encounters another crystal of tourmaline in the same position as the first, the polarized light passes through this also, but if the second one is rotated through 90° about the line of light as an axis, it completely cuts off the light. The first of these crystals is called a polarizer and the second an analyzer.

While there are many useful and interesting scientific applications of polarized light, there is one of more especial interest because it illustrates how this, one of the most abstruse phases of theoretical science, has been brought to such a degree of simplicity in

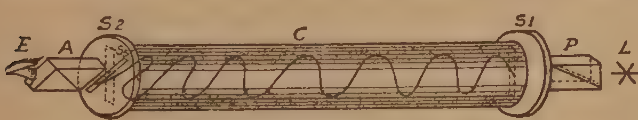
its application that a tyro can use it. It is the best means of standardizing and testing sugar.

If light from L in diagram (A) is polarized by the crystal P, so that its vibrations pass through the vertical slit S_1, they will also pass through the vertical slit S_2; and if the analyzer A is in the same

(A) POLARIZED LIGHT

Diagram to illustrate its usefulness in testing a solution of cane sugar

position as P, the light will enter the eye E and the slit S_1 will be seen. If a tube or cell C, (B) with glass ends, containing a solution of sugar, is interposed between S_1 and S_2, the polarized light that before passed through S_2 and the analyzer A no longer does so. But if A and the slit S_2 are turned through an angle into the position S_3, the light is transmitted, and S_1 is again visible. The vibrations that were vertical at S_1 arrive at A in the plane of S_3, or, as it



(B) POLARIZED LIGHT

The plane of polarization is rotated through a solution of sugar

is said, the plane of polarization has been rotated by the liquid. With a standard length of cell, the amount by which the plane is rotated varies with the concentration of the sugar solution. But not all sugars are equally effective. With a given percentage of any kind in solution, its sweetening quality is

determined by the angle through which S_2 must be turned to permit the passage of light to the eye from S_1.

Various other substances, either in crystalline form or in solution, rotate the plane of polarization, and are distinguishable not only by that property, but they reveal the further remarkable fact that while some rotate the plane to the right, others cause it to turn to the left. While cane sugar rotates the plane to the right, grape sugar turns it to the left.

In diagram (B), if the tube C is one decimeter (about four inches) in length, and contains a solution of cane sugar of one gram to the cubic centimeter in water at 68° F., the angle through which S_2 must be turned to the right to reach the position of S_3 is 66.5°; if the tube had contained a solution of the same proportion of sulphate of quinine in alcohol at 63° F., it would have been necessary to turn S_2 57.5° *to the left* for the light from S_1 to pass through.

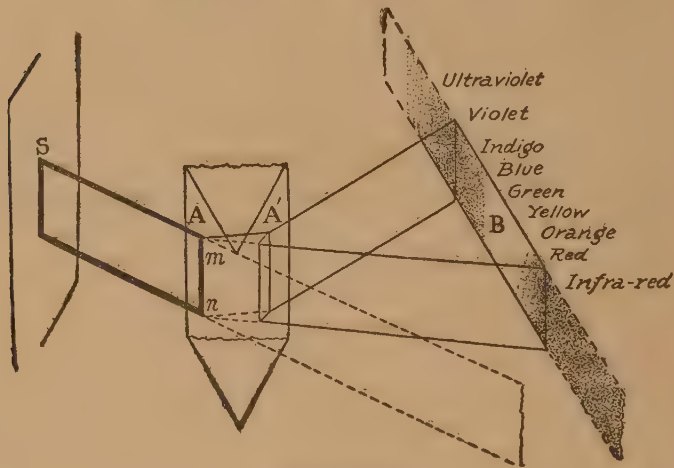
CHAPTER XLV

COLORS—THE SPECTRUM

UP to this point we have treated light as if it were of only one kind; and the phenomena we have considered are for the most part characteristic of light in general.

Newton's famous experiment with the prism brought out the fact that ordinary white light—sunlight—is highly complex, and that its components may be separated. Through a small round orifice in the shutter of a darkened room he admitted a beam of sunlight which, after passing through a prism of glass, was expanded into a broad band of colors. This experiment was one of the landmarks along the path of scientific progress, and yet the great philosopher just failed, as other famous experimenters have failed, in their pioneer efforts, by some seemingly trifling circumstance, to find the key of the door to which it pointed, and behind which lay a world of nature's secrets awaiting revelation. If he had used, as, long afterward, his successors used, a narrow slit instead of a round opening to admit the light, he would have learned, as they learned, that the results of such decomposition of light are simpler and sharper, and their interpretation is clearer when thus brought about. This fact was not discovered, however, until the beginning of the nineteenth century, or a hundred and thirty years after Newton's discovery.

A strip of light coming from a slit S, as illustrated, and falling upon the face A of a triangular glass prism in a line *mn*, is refracted as it enters the prism; also it meets the face A′ at a different angle from that which it would make if A′ were parallel to A, consequently, after emerging from this second face the light is not parallel to the incident strip from S, but is spread out into a band B which,



THE PRISM

A prism resolves a beam of white light into the separate colors

falling upon a white wall or screen, displays the beautiful series of colors known as the *spectrum* —if of sunlight, the solar spectrum. Some portions of the light have undergone much greater refraction than other portions; the most refracted is violet, then come in order other colors, and if the slit is of moderate width, say a quarter of an inch, each color merges into the next with no sharp line of distinction, but delimited somewhat arbitrarily as violet,

indigo, blue, green, yellow, orange, and red. In the figure on page 331, something of this partition of the incident light from I occured at O, and as all the portions emerging at S were parallel, so long as the eye receives all the components of a single beam from I the separation into colors would not be perceived. It is demonstrable as a mechanical fact that shorter waves would be retarded and refracted more than longer ones in passing through a denser medium. The spectrum at once revealed the fact that some part of the light was retarded by the glass more than other parts, or that, while light of all colors traverses interplanetary space with the same speed, in passing through material bodies the velocity is different with light of different colors. That means that since the form of disturbance in the ether that constitutes light at all is that of waves, some of the waves are shorter in length and briefer in period than others; and so violet light is due to shorter waves than red light.

It is possible, by several independent methods, to determine what length of wave corresponds to any position in the spectrum, and therefore to determine between what limits of wave length the different colors are comprised. All light waves are very short. To express their length in moderate numbers a unit of length is used that is so short that a thousandth of an inch would be as great in comparison as a two-foot rule would be to an inch. This unit, called a *micron*, is one-thousandth of a millimeter, and the length of one wave of the yellow light that is best for vision is a little more than half of a micron. The average length of the waves in the entire visible spectrum is about six-tenths of a micron.

As light travels through space at the rate of 186,000 miles in a second, there are about 500 millions of millions of such waves produced within a second, or that number of vibrations per second in the molecule causing waves of that length. The shortest wave of the visible spectrum, the extreme violet, is 0.39 micron, and the longest, the extreme dark red, is 0.81 micron; or the most rapid vibrations to which the eye responds are a little more than twice as frequent as the slowest. In the language used for sound vibrations, this is a little more than an octave. When it is remembered that the ear perceives sounds through a range of over seven octaves, it is seen that its sensibility is far more extended than that of the eye.

ONLY THE SPECTRUM OF AN INCANDESCENT SOLID OR LIQUID IS CONTINUOUS IN COLOR

In testing the light emitted by various substances it was found that every substance produces its own peculiar spectrum; but this characteristic spectrum is only formed when the light is that of the substance in a gaseous state. So long as the luminous body is solid or liquid, though brilliantly incandescent, its spectrum is a continuous band of colors ranging from violet to red.

The light is ascribed to ether waves which are produced by vibrations of the molecules of the luminous body, and the different colors mean different rates of vibration. In solids and liquids, evidently the impacts of the molecules come so closely upon one another as to excite ether vibrations of all frequencies. Not, however, until they attain a certain degree of rapidity, do they affect the eye as color, and color as a sensation begins with dark red. Beyond a certain

frequency, the eye no longer responds to them and the light, *as such*, is no longer perceived; this upper limit is where the violet deepens into darkness. Moreover, the dark red will appear whenever a body is heated up to a certain temperature, about 1,000° F., and with further rise of temperature it brightens until it becomes a dazzling white. The temperatures at which it passes through the various colors are approximately:

	C.	F.
Red—just visible.....	525°	977°
Dull red	700°	1292°
Cherry red	900°	1652°
Orange	1100°	2012°
White	1300°	2372°
Dazzling white.......	1500°	2732°

In this last condition the light combines all the colors of the spectrum, and results from the successive addition of the more and more rapid vibrations of the ether as the temperature rises, and the impacts of the molecules become more frequent.

HOW THE LIGHT FROM A GAS DIFFERS FROM THAT OF A SOLID OR LIQUID; SPECTRA OF VARIOUS SUBSTANCES

When a molten substance is further heated and driven off in luminous vapor, or when crystals are volatilized by intense heat, the spectrum undergoes a marvelous change. If it is obtained from an illuminated *narrow* slit, it is no longer continuous, but consists of separate bands of color, each band at its place in the spectrum corresponding to its own color. Each band is an *image of the slit,* and results from light of a definite wave length. The spaces between the bands are dark. If the slit is wide, neighboring

bands may overlap and no longer appear separately, so for definiteness it is necessary to place a converging lens between S and the prism, where it will focus S on the screen. Then if S is narrow it has a sharp narrow image for waves of nearly the same refrangibility.

If common salt (sodium chloride) is burned in a nonluminous gas flame, the chlorine is scarcely noticeable, but the vapor of the sodium makes a strong though pallid yellow light, of which the spectrum is a bright yellow band. If the slit of light is very narrow, the band is found to be double, a narrow dark space separating the two parts.

SPECTRUM OF LIGHT FROM SODIUM VAPOR

If any source of light contains sodium in it, even in a minute proportion, the spectrum will reveal its presence by this bright line; and the presence of other elements will likewise be evidenced by their own peculiar lines in the spectrum. It was by such means that various terrestrial elements have been identified in the sun's atmosphere. The solar spectrum, when produced by an illuminated narrow slit, is not continuous, but is crossed by numerous dark lines or gaps. These dark lines are known as Fraunhofer's Lines, from the physicist who first investigated them, and are due to gases in the outer atmosphere of the sun, which absorb the radiation of their own period from the hotter body within, and so are relatively less intense in their vibration than other constituents of the solar atmosphere; they are, therefore, relatively dark in the spectrum. Many of the dark lines have been identified with the bright line spectra of various known substances, which correspond exactly to them in their place in the spectrum.

That separate rates of vibration should be possible in a gas and not in a solid or liquid may be accounted for by the fact that a molecule of any substance has its own peculiar way of vibrating, and for this mode to become apparent it is only necessary that there shall be a sufficient interval between two collisions of one molecule with another for the molecule to undergo and exhibit its own "fundamental" mode of vibrating, and this is possible in a gas where it would not be so in a liquid or solid. Solids can be thus converted into a luminous gas in the electric arc, but ordinary gases must be held in some transparent container, and cannot be sufficiently heated to obtain their spectra. A better means has been devised. The gas is inclosed in a slender tube of glass; this is then exhausted to a high vacuum and sealed shut. Into the ends of the tube enter platinum terminals as electrodes which are connected with the poles of an induction coil. When this is put in operation the molecules of gas are electrified, negatively at one pole and positively at the other, and they mutually repel one another with violent collisions. With an appreciable free path, the light resulting is such as corresponds to their own peculiar rates of vibration.

COLOR AND THE COLOR OF OBJECTS

Light, like sound, must be regarded both as a physical occurrence and as a physiological sensation. In the former view its peculiarities are all accounted for by ether vibrations of different frequencies and intensities, producing waves of various lengths. The disturbance of the ether is caused by vibration of the molecules of bodies emitting light, and is more or less hampered by the molecular nature of bodies which it encounters.

Any color is "light," but an object may be of different color under different circumstances, depending upon the light in which it is placed, and the nature of the surface or molecular structure of the body. Light containing all the color constituents is called white light; that containing only one color is monochromatic; and each color has its own wave length.

If light of any kind, simple or complex, falls upon a body, and is transmitted by it to an observer on the farther side, the body itself and things seen through it will have the color of the light that is transmitted. What that will be depends upon the power of the substance to *absorb* light of particular kinds. Of course, neither the light that was reflected from the body, nor that which was absorbed by it, came through at all; if all was reflected, whether regularly or irregularly, the body would be bright on the light side and black on the other; if all the light were absorbed it would be black (or invisible) from either side; if it absorbed certain colors its appearance would be determined by the degree of absorption and the portion of the light not absorbed.

Generally, a nonluminous body, i.e., one not itself emitting light, can only give back light of the kind that it receives, and usually not all of that. There are some exceptions to this, of which we shall speak later. The body commonly has some selective power in consequence of which it retains light of one color more than another. If it is illuminated by light of only one color, the body is either of that color or none—i. e., black. In white light human faces and hands are white, containing various colors combined, and are vivified by a further

tinge of red; if illuminated only by sodium light, they have a ghastly hue, and clothing, furniture, or materials of various colors appear only yellow, more or less intense, or black. The dreariness of a world illuminated by light of only one color would be inexpressible.

Light falling upon a prism at a definite angle will be refracted into a definite place in the spectrum, this place depending on the wave length of that particular part of the composite light and on nothing else about it. Every part of the spectrum corresponds to its own particular wave length. If this length is 0.58 of a micron, it unquestionably means yellow light; if it is 0.47 of a micron it is infallibly blue; if 0.66 of a micron it is certain to be red. Every wave length between 0.4 and 0.8 of a micron means some unvarying color. *That is the physical meaning of color*, but it is not the whole story—while a definite wave length means a particular color, that color does not always mean just that wave length.

THE INVISIBLE PORTION OF THE SPECTRUM

Since both ends of the solar spectrum trail off into darkness, neither the violet portion nor the red contributes much to seeing. The most luminous part is the greenish yellow, for which the wave length is about $\frac{1}{46,000}$ of an inch. In the *ultra*-violet region are detected waves shorter and shorter, down to about one-half the length of the yellow; while far into the *infra*-red, waves have been measured more than five times as long as the yellow.

The short waves are more actinic, and produce stronger photographic action than the long ones, the most intense effect being produced in the ultra-

violet, while the yellow and longer waves have feeble photographic action. By photography radiation from various sources has been detected in waves as short as 1/20 of the length of yellow. The long waves are more effective in heating, and by exceedingly sensitive apparatus applied to the spectra of hot bodies waves more than 400 times as long as yellow have been measured. It is now known that the radiant energy in the infra-red portion of the solar spectrum is more than 100 times that in the ultra-violet.

PRIMARY COLORS

Whatever theory may be correct as to the nerve stimulus that results in any particular color sensation, the *red, green,* and *violet* of the spectrum are called the *three primary colors,* because all hues or colors can be perceived by the eye on mixing these three in proper proportions. Light, then, may be any color; but color, as light, must not be confounded with color as a sensation; the sensation of blue is not always due simply to the short waves nor red to the longer ones.

COMPLEMENTARY COLORS

Any portion of the complete spectrum of white light might be separated from the rest, and each of these two parts then compounded into one resultant hue; these two results, if united, would reproduce the original white, for such union would include the entire spectrum, so each portion is *white minus the other.* Two such colors which together make white are said to be "complementary." Any one color of the spectrum is complementary to the color that would result from the combination of all the rest. If

the colors named in the first column following are chosen from the spectrum, those in the second column are their complementaries:

Spectrum	Complementary
Red	Bluish Green
Orange	Greenish Blue
Yellow	Blue
Green	Dark red
Blue	Yellow
Violet	Greenish yellow

CHAPTER XLVI

COLOR PHOTOGRAPHY

FROM the time that a permanent sun picture was first produced in black and white, it has been the dream of photographers to reproduce scenes in the colors of nature. Again and again they have seemed on the verge of success—more than one process has been partially successful, one or two highly so, but the best are far from perfect, and they are too complicated in theory to be given here, nor can they be used in any popular way. The difficulty is to obtain permanent pictures in color, that can be easily and cheaply multiplied. The scenes, however, can be photographed and then exhibited in colors that are remarkably faithful reproductions of the original.

The principles on which this is accomplished involve a so-called "three color process." Regarding every color as a composite of red, green, and violet, in various proportions, three clear gelatin films are stained in these colors. Each of these films then transmits its own color and intercepts the others. Three camera pictures of the same scene are taken, one with the red filter before the lens, one with the green, and one with the violet. The light through the red screen acts upon the photographic film, and darkens it more or less, where the image should be for the red in the original scene; the rest of the *negative* has received no light and is clear. From this, by photographic printing, a *positive* is made, which

is more or less clear where the red light fell, and the rest is dark. If this is projected upon the screen or viewed directly by white light through a red filter, like that with which its negative was taken, it will display the original scene *so far as the red was a part of it.* Another such positive from the negative made by the light through the green filter, and projected or viewed through a corresponding filter, will bring back the green of the original, and a similar procedure reveals the violet. If these three are superposed on the screen or are all viewed together, the *primary colors* blend to make the composite of the original scene.

This is a true mixing of colors.

Two complementary colors, in varying proportions, would approximately produce all the others, and would give fairly good reproductions. This has been applied with considerable success to motion pictures. A difficulty lies in the fact that in taking the pictures from nature, no photographic film is equally sensitive to all colors, and therefore a longer exposure is needed for the red, say, than for the violet.

COLORS OF PIGMENTS; THREE-COLOR PRINTING

It has been no less desirable to reproduce color scenes from photographs by using various colors of printer's ink, which is a pigment, than to photograph in color directly. When paints or pigments are mixed, the resulting color is not that of mixing the elementary colors of the pigments. A blue paint and a yellow, instead of making white when mixed, are green; and other mixtures will give results equally at variance with those which would follow the blending of the corresponding colors. If a pigment is yellow, in white light it is so because it *absorbs* all light,

except yellow; and the action of all pigments is like that. A surface covered with such yellow paint, and not glossy, looks black in blue-violet light; one painted dark red is black in green light; and one in peacock blue is black in red light; one printed in ink of these three colors superposed is black in white light. An ostrich feather dyed a rich blue absorbs all the rest of white light and returns only that color to the eye. If it is illuminated by color lacking blue, it absorbs the color, and returns none to the eye. The complementary of the blue is orange-yellow; this is all of white light except blue, and the feather, illuminated by an orange-yellow electric lamp bulb, is black. The lighting systems adopted for special effects in theaters, banquet halls, and other places of public functions, sometimes play havoc with the color schemes of costumes and cosmetic adornment of guests and participants.

Facts like these are guides in color printing. Suppose three primary filter screens are blue-violet, green, and red. Through each of these a negative of a scene or subject in color is taken. When the plate taken through the green filter is developed, where the green light fell the photographic film will be darkened and hardened and high; where no light fell it will be clear and thin. From this negative an electrotype of copper is made and backed from which to print. This is a positive, or reverse of the negative, being high where this was low, and conversely. The high places will print on the paper, and these are the places where there was no green in the picture; this plate therefore must not be printed in green. But there were possibly other colors in these places, so this plate must be printed in ink that will return any of white light except

green—that is, in the *complementary* of green—a crimson ink. In like manner the printing-block positive prepared from the negative that was taken through the red filter, is printed with a blue ink that is its complementary, and that taken through the blue-violet filter is printed with ink of its complementary hue, yellow.

When these three suitably inked blocks all make their imprint on the same paper, and the composition is viewed in white light, red appears where it is *not absorbed,* and that is where it was in the original subject; and so with each of the other colors or with the tints resulting from their combination. Where the scene was white, no ink touched any of the printing blocks and the printed picture is white; where it was black every block printed, all the light is absorbed, and the picture is black.

CHAPTER XLVII

OTHER INTERESTING FACTS ABOUT LIGHT

A GOOD-SEEING TELESCOPE HAS TO BE SPOILED TO FIT IT FOR ASTRONOMICAL PHOTOGRAPHY

A TELESCOPE with a twelve-inch objective had done good service in astronomical observation, but was to be replaced by a larger one, and was itself to be used for celestial photography.

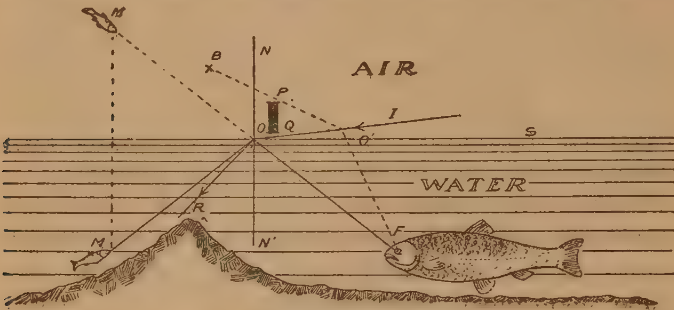
When a sensitive plate is placed in the focus of the objective, it receives the image, and on being developed it reveals bodies and detects peculiarities so effectually as to make this one of the most important methods of astronomical research. But from what we have seen of the unequal refraction of the different colors by a prism or lens, the violet portion of the light is brought to a focus nearer the lens than the red portion. A double convex lens produces this confusion of color. If the image is focused for the red or yellow it is fringed with blue and violet, and this portion of the light does not help in making the image. Even orange-red and greenish yellow do not focus together, and these with the intervening yellow constitute nearly all the luminosity of the spectrum. But a lens may be corrected so as to bring any two portions of the spectrum into the same focus. A converging lens of crown glass is accompanied by a lens of flint glass that is diverging. This may be so ground as to

bring two portions of the spectrum into parallelism without wholly counteracting their refraction. Thus an image will still be produced, but it will not have a confusion of those colors for which it is corrected. Such a combination of lenses is called *achromatic*, and is used in all high-grade optical instruments. If the color correction has been made for the light from orange-red to greenish yellow, the lens is improved for seeing; but this part of the light has little photographic effect; that comes chiefly from the blue, the violet, and the ultra-violet. Accordingly, the lenses for photographing, especially with faint light, are most effective when so ground as to compensate or correct for the part of the spectrum extending from blue considerably beyond the visible violet; so the first thing to be done with the telescope mentioned above, to prepare it for photographing, was to ruin it for viewing, and with proper reshaping of its curved lens surfaces it was improved for use in this method of research.

LIGHT WILL NOT ALWAYS PASS FROM ONE TRANSPARENT MEDIUM INTO ANOTHER; TOTAL REFLECTION

A ray of light in air, coming obliquely to the surface of water, will enter the water even if it is almost horizontal, and will be bent downward, as IOR in the figure on page 374. If the ray had proceeded from R to O it would have passed into the air along OI. If R had been a little more nearly horizontal, making the angle RON′ 48° 35′, OI would have been exactly in the surface OS; and if the angle RON′ were any greater than this as, e. g., MON′, the light from M would not emerge into the air, but would be totally reflected back into the water. Only that

light from a point in the water would pass through O into the air, which lies within the cone around ON′, formed by lines making an angle equal to MON′. M would be visible to an eye at F by the reflected ray OF, and would appear to be at M′. If a barrier PQ intercepted the direct line of light from an object B in the air to an eye at F, the eye



LIGHT MAY BE DEFLECTED

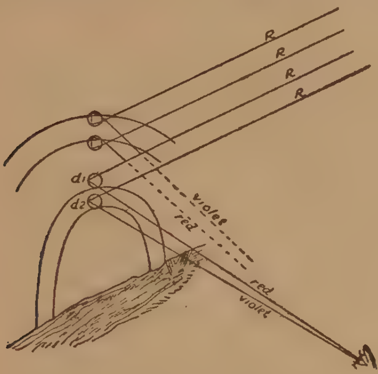
would nevertheless see B by the refracted ray O′F. Thus the eye at F is said to "see around the corner" at P. Other curious effects have been shown in so-called "fish-eye views."

THE RAINBOW

This beautiful object never fails to draw expressions of admiration from those who witness it, but *no two persons see the same rainbow.* It is the unequal refraction of the different colors by raindrops that causes the rainbow, and it is the total reflection of light as described in the last article, together with refraction, that makes the bow visible.

In the figure (A), d_1 is one of many raindrops, in such a position that a ray of sunlight R entering it is refracted, then totally reflected, and emerges, fol-

lowing the path r, a, b, c, d (B). At each refraction its spectral colors are separated. Some drop as d_1 is at a height such that the red, on emerging, reaches the eye E from d_1, and a series of drops which all cause the same angular deviation in the path of light from the sun to the eye, will form a circular band around the line from the eye to its center. One series of such drops gives to the eye a band of red in a circular form. Somewhere below d_1 is



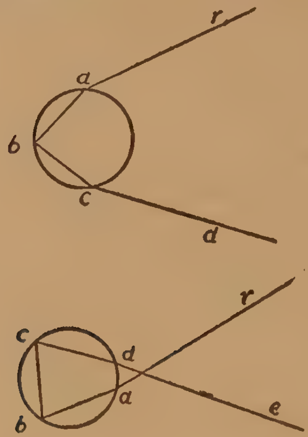
(A) THE RAINBOW EXPLAINED

another position from which the violet ray, more refracted, reaches the eye, and there is an arch of violet, the space between these being occupied by the intermediate colors of the spectrum; and thus is produced the "primary" rainbow.

Another bow, called a "secondary," is sometimes seen above the primary. In this the light has undergone two internal reflections, taking a course like r, a, b, c, d, e, in figure (B). Here, the ray reaching the eye from the upper drop is the more refracted, or is the violet, and the colors in this arch appear in the reverse order from those in the

primary. This bow is fainter and less perfect than the primary.

If one stands on a height above a valley in which mist is rising, or looks down upon spray of a waterfall upon which the sun is shining at the proper angle, he may see the rainbow arch curved in the



(B) THE RAINBOW EXPLAINED

opposite direction, and with rain falling from above him to a level far below him, a complete circle is possible.

CAN TWO LIGHTS PRODUCE DARKNESS? INTERFERENCE OF LIGHT

Since the meeting of two sets of waves may result in reenforcement or interference, we might expect two portions of light to produce darkness, just as two sounds produce silence. For complete interference, however, the waves must be of equal intensity, and for the interference to be maintained for any considerable length of time they must be

of very nearly, if not exactly, the same period or length. In sound it is easy to get waves of only one period, that is the case with the fundamental tone of any sounding body. Light, to have a corresponding action, must be monochromatic.

Where a layer of oil has spread out into a very thin sheet, as it does on the surface of water, it displays rainbow colors over its surface. This is due to interference, but it occurs in this wise: Some light of all colors is reflected from the upper surface, some enters the oil, is refracted, is slightly dispersed into colors, is reflected at the second surface, and again emerges into the air parallel to the first reflected portion. If the film of liquid is of such a thickness (or rather, of exceeding thinness) that the emergent red is one-half a wave length behind the red first reflected, these will interfere, and the light entering the eye *from that part of the surface* will lack red, and will be of the complementary color, green. Near this part of the surface the green will interfere and there, to the eye, it will have the complementary hue, red; and somewhere near that will be the complementary of violet; altogether the oil surface may show separately all the colors that compose the light shining upon it. This is the way the beautiful colors of soap films arise.

If the surface were illuminated by light of only one color, say yellow, the yellow would be canceled wherever the second reflection was one-half, or three halves, or five halves, or any odd number of half wave lengths behind that in the first reflection, and the field of view would be zones of yellow and black. The two lines of reflection have the same effect as if the light had proceeded from two

sources slightly different in position. The black regions are *darkness resulting from the interference of two streams of light.* Light might thus be separated and made to interfere by refraction, and also by the slight deviation called "diffraction," which it undergoes in passing an edge of a body.

HOW LIGHT IS PRODUCED BY X-RAYS; BY CATHODE RAYS; BY RADIATION IN THE INVISIBLE PART OF THE SPECTRUM; BY RADIOACTIVITY. FLUORESCENCE; PHOSPHORESCENCE

It is not uncommon to hear the remark "I saw the X-rays" from some one who had witnessed an exhibition of their action. Yet X-rays are not visible. When they strike upon certain substances they cause these to light up in a color peculiar to each substance: barium platinocyanide — a yellowish white; calcium tungstate—a bluish white; glass—a blue, violet, or green, depending upon the mineral in the composition of the glass. Many substances, vegetable and mineral, which are colorless or invisible in the spectrum from green to red become luminous with a distinct color when placed in the blue or violet light, or still more so in the ultra-violet, the *dark* part of the spectrum.

It has been thought that this effect was a change in the refrangibility of the light falling upon the bodies; that light of extremely rapid vibration was reduced in frequency, and the ether waves were changed in their period just as, with polarized light, they are altered by some substances in their plane of vibration. In whatever way it may be excited, the light, when emitted by these, is of exactly the same character as light of the same color coming from bodies of any kind in ordinary illumination,

or self-luminous. The more generally accepted explanation now is that the light emitted by these bodies is not the light that shone upon them and was changed in character, but that the substances have such peculiarity in their molecular action that the incident light has set the molecules vibrating in a period of their own. This is not in accord with the principle of resonance, but fits in with the fact that these bodies emit the same kind of light under bombardment by material particles.

When one sees X-rays, as he supposes, he simply sees the body that has become luminous on its own account, under the impact of the X-rays.

Emission of light of a different rate of vibration from that which causes it is *fluorescence*.

In much the larger number of instances fluorescence is excited by light of very high frequency, and the resulting light is lower. X-rays are etheric pulses a hundred times as rapid as violet light. Of course when fluorescence results from the radiation in the ultra-violet, and is a visible color, the rate is reduced, but there are some instances in which the fluorescent light is of higher frequency than that which caused it.

If green leaves are macerated for some time in alcohol, the solution is a fine, clear green, but when held in the violet or the ultra-violet of the spectrum it is deep red. Most of the aniline dyes fluoresce, some of them brilliantly; a solution of eosin which is red in ordinary light is green in nearly all the separate portions of the spectrum; a solution of sulphate of quinine which is colorless by transmitted light is blue in reflected light, or when held in the ultra-violet of the spectrum. This appearance in reflected light, like that with petroleum, mentioned

in the beginning of this chapter (page 323), is due to fluorescence.

The effect is produced not only by light rays, but by cathode rays also. Many minerals, when inclosed in a Crookes tube and exposed to cathode rays, fluoresce brilliantly. The same effect is produced by the rays from radium, and all radioactive substances. In both the latter cases it is known that the effect arises from direct impact of innumerable electrons — bodies of almost infinitesimal size. Phosphorescence, the light with which bodies glow in the dark after they have been exposed to strong light, is thought to be of the same nature as fluorescence, except that in the latter the molecular vibration stops with the cessation of the exciting cause, while in the former it persists sometimes for several hours.

This, again, is quite different from the light with which so-called "radium watch dials" shine in the dark. These are shining in the light just the same as in the dark, the luminosity coming from the emission of the minute radium particles of the salt that has been applied to the surface of the dial. Radium and other substances discharge multitudinous fine particles which, like X-rays and cathode rays, evoke fluorescence in many minerals, and that light continues so long as the fluorescent material is in the presence of the radioactive substance.

GLOSSARY

TECHNICAL TERMS AND COMMON WORDS USED IN A TECHNICAL SENSE

Absolute.—Not derived from something else of a like nature; as absolute units; absolute system.

Acceleration.—Time-rate of change in velocity; as the number of *feet per second* by which the velocity of a body is increased or decreased in a second, in a given direction.

Actinic.—Capable of producing chemical change by radiation, as the action of light in photography.

Adiabatic.—Not permitting heat to pass through; an adiabatic change in a body is one that occurs without gain or loss of heat.

Amplitude.—The extreme distance which a vibrating particle departs from its neutral position.

Aneroid.—Without moisture; an aneroid barometer is one that shows variations of atmospheric pressure by the elasticity of its material instead of a column of liquid.

Anion.—Ion which appears at the positive terminal of an electrolytic cell.

Anode.—The + terminal at a gap in an electric circuit from which the current or electric discharge passes on toward the — terminal or cathode.

Anticathode.—A portion of electrical apparatus receiving the discharge from the cathode, without being necessarily a part of the electric circuit. When bombarded by cathode rays the anticathode becomes a source of X-rays.

Atmosphere (*An*).—Pressure per unit area equal to that of the atmosphere; a "standard atmosphere" exerts a pressure of 1,013,250 dynes per square centimeter.

Battery.—An assemblage of cells to send an electric current, or of Leyden jars to form a condenser for static electricity.

Body.—Any limited portion of matter, whether solid, liquid, or gaseous.

Cathode.—The — terminal at a gap in an electric circuit, toward which the current or discharge of electricity passes from the anode or + terminal.

Cation.—Ion which travels with an electric current and appears at the negative terminal of an electrolytic cell.

Cell.—A jar or vessel containing two or more substances that produce electromotive force.

Conservation.—Continuance without gain or loss.

Electrode.—A terminal at a gap in an electric circuit, toward which or from which an electric discharge proceeds.

Electrolysis.—The decomposition of an electrolyte.

Electrolyte.—A liquid whose molecules are decomposed by the passage of an electric current through it.

Electromotive Force.—The action of a body or combination of bodies which results in an electric difference of potential between two points.

Frequency.—The number of occurrences per second; in sound or vibration, the number of vibrations per second.

Interval.—In sound, the interval between two notes is the ratio of their frequencies.

Ion.—An electrified particle produced by the electrical separation of molecules or atoms.

Isothermal.—Without change of temperature.

Kinematic.—Of motion, without reference to force or mass.

Kinetic.—Of, or due to motion, usually in connection with mass moved or the forces moving it.

Make and Break. A mechanical contrivance to open and close an electric circuit repeatedly, like the vibrator of an electric bell.

Medium.—Substance through which physical action is transmitted; as air is the medium that usually conveys sound to the ear; the universal ether is the medium that transmits light, etc.

Mil.—One thousandth of an inch (used to measure the diameter of a wire). *Circular Mils,* the square of the diameter of a wire in *mils.*

Moment.—(Of a force about a given point), the product of the intensity of the force by the perpendicular distance from the line of its action to the given point.

Particle.—A body so small that, in relation to other bodies and distances considered along with it, its size may be neglected.

Period.—The length of time required for one complete cycle of operations. In vibratory phenomena, the time required for one complete vibration.

Polarization.—In light, reducing vibrations in various directions to some definite direction; in electricity, an action in a cell which tends to send a current in a direction opposite to that instituted by the cell itself.

Potential.—A condition at any point, such that work has to be done on a body to bring it to that point or to remove it from the point.

Potential Difference.—A difference in condition at two points, such that work has to be done to transfer a body from one point to the other.

Primary cell or *battery*, one which will send an electric current by action of its constituents, without requiring to be put into condition by some other agency. *Coil*, a coil of wire in which an electric current is started or stopped from some source, thereby inducing an electromotive force in another conductor.

Rate.—Ratio of amount accomplished to time or distance used in accomplishing it. *Time-rate* is amount accomplished *per unit of time;* the amount done in a given time divided by the time occupied in doing it. *Space-rate* is amount accomplished *per unit of distance;* the total amount done divided by the distance traversed in doing it.

Ray.—In light, the direction along which light moves from one point to another; in electricity, a line of electrified particles discharged from an electrode, as cathode rays, etc.

Regelation.—Re-freezing; the freezing together of two surfaces that had been separated by melting under pressure.

Rheostat.—A contrivance for introducing resistance into an electric circuit or withdrawing resistance from it.

Secondary cell or *battery*, one that is put into condition to send an electric current by being charged from some other source. *Coil*, one in which an electromotive force is induced by varying the current in a neighboring conductor.

Specific.—Quality or property in bodies, that becomes definite by its relation to some standard body, as specific gravity, specific heat, etc.

Static.—Not in motion, as static electricity. In mechanics, *statics* deals with forces in their relation to equilibrium of bodies.

Thermodynamics.—Relation of heat to mechanical work.

Thermostat.—Instrument that automatically prevents the temperature from rising or falling beyond a certain degree.

Torque.—The effective moment of a force or forces, in tending to produce rotation.

Unit.—A defined quantity by which to measure bodies or actions.

Velocity.—Rate of travel in a given direction; as *feet per second*, etc.

Wave.—The entire disturbance in a medium, resulting from one complete vibration of a particle or body.

Wave-front.—The surface bounding the disturbed portion of a medium at any instant, when the disturbance is due to the progress of waves through it.

Wave-length.—The distance between a wave front and the next wave front having points in the same stage of their vibration. This is the distance the disturbance progresses, in the period of one vibration of the disturbing body.